Influence of calcium on yield and quality aspects of potatoes (*Solanum tuberosum* L.).

By

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: March 2017

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Abstract

The potato (*Solanum tuberosum L.*) is an adaptable crop, and modern varieties make its cultivation feasible in numerous parts of the world. The high production potential of the potato ensures that it has the potential to contribute significantly to the world's food requirements. Correct fertilisation is an important factor in potato production to obtain maximum yields and high quality tubers. Calcium (Ca) is an essential plant element and plays a significant role in the potato plant by maintaining cell membrane and cell wall structure. Recent studies have indicated that tissue Ca level is linked to the quality of various fruit and vegetable products. In the case of potatoes a reduction in tuber internal defects and an improvement in storability can be expected with an increase in tuber Ca. The mechanism of Ca uptake by the potato plant and translocation of Ca within the plant however inhibits the uptake of Ca into the tuber. Thus the present study aims to evaluate the methods to improve Ca tuber content and tuber quality aspects.

Potato seedlings of four cultivars (Mondial, Sifra, Lanoma and Innovator) were used in a tunnel where different concentrations of Ca (1.1, 3.2, 6.6 and 9.8 meq Ca L^{-1}) were applied. Tuber mass, shoot fresh mass and shoot dry mass was affected by the Ca application levels and also differed between the cultivars. Mondial, a popular South African cultivar, performed best in terms of tuber yield. Application of 3.2 meq L^{-1} Ca through drip irrigation was most beneficial to yield parameters (tuber yield, shoot fresh mass and harvest index). To study the Influence of different calcium application levels on potato plants under low temperature growing conditions, potato seedlings of cultivars Destiny and Lanorma, were transplanted into 3 m^3 bins containing three different soils (sandy, sandy loam and loam) during the winter season. Three calcium application rates (1.1, 3.2 and 6.6 meq Ca L^{-1}) were applied through drip irrigation. The interaction between Ca application levels and cultivars significantly influenced tuber mass, shoot fresh and dry mass. The influence of Ca as a foliar application on the growth, yield and quality aspects of potatoes was also investigated. Two cultivars (Lady Rosetta and Mondial) were used in a trial where different concentrations of Ca were applied as foliar application or soil drench, during tuber bulking and maturation. None of the parameters measured; tuber fresh mass, tuber number, specific gravity, percentage dry mass or chemical composition was significantly influenced by either the foliar application or soil drench calcium applications. It appears that supplemental Ca applied at these rates and time of plant development has no added benefit on yield or quality aspects of potato tubers.

Calcium fertilisation can positively affect both yield and tuber quality but the rate and method of application are of utmost importance. Cultivars also respond differently to Ca application and producers should bear this in mind.

Uittreksel

Die aartappel (*Solanum tuberosum* L.) is 'n aanpasbare gewas, en moderne variëteite maak die verbouing daarvan prakties in talle dele van die wêreld. Die hoë produksiepotensiaal van die aartappel verseker dat dit oor die potensiaal beskik om 'n betekenisvolle bydrae tot die wêreld se kosbehoefte te lewer. Korrekte bemesting is 'n belangrike faktor in aartappelproduksie en is noodsaaklik om maksimum opbrengste en hoë gehalte knolle te lewer. Kalsium (Ca) is 'n noodsaaklike voedingselement en speel 'n belangrike rol in die aartappelplant deur die handhawing van selmembraan en selwand struktuur. Onlangse studies het getoon dat Ca inhoud van plantweefsel nou gekoppel is aan die kwaliteit van verskeie groente en vrugte. In die geval van aartappels word 'n vermindering in knol interne defekte en 'n verbetering in opbergings vermoë verwag met 'n toename in Ca in die knol. Die meganisme van Ca opname deur die aartappelplant en translokasie van Ca in die plant beperk egter die opname van Ca in die knol. Die doel van die huidige studie was dus om metodes te evalueer om die Ca inhoud van die knol en knol gehalte aspekte te verbeter.

Aartappel saailinge van vier kultivars (Mondial, Sifra, Lanoma en innoveerder) is gebruik in 'n proef waar verskillende konsentrasies van Ca (1.1, 3.2, 6.6 en 9.8 meq Ca L^{-1}) toegedien is. Knolmassa, halm vars en droë gewig is beïnvloed deur die Ca toedieningsvlakke en het ook verskil tussen die kultivars. Mondial, 'n gewilde Suid-Afrikaanse kultivar, het die beste gevaar in terme van knolopbrengs. Toediening van 3.2 meq L^{-1} Ca deur drupbesproeiing was baie voordelig in terme van knolopbrengs, halm vars gewig en oesindeks. 'n Proef is ook gedoen om die invloed van kalsium peile op aartappelplante onder lae temperatuur groeitoestande te evalueer. Aartappel saailinge van kultivars Destiny en Lanorma is geplant in 3 m^3 dromme gevul met drie grondtipes (sanderige, sandleem en leem). Drie kunsmis toedieningspeile (1.1, 3.2 en 6.6 meq Ca L^{-1}) is toegedien deur drupbesproeiing. Kalsium toedieningspeile en kultivars het 'n groot effek gehad op knolgewig, halm vars- en droëgewig. Die invloed van Ca as 'n blaarbespuiting op die groei, opbrengs en kwaliteit aspekte van aartappels is ook ondersoek. Twee kultivars (Lady Rosetta en Mondial) is gebruik in die proef waar verskillende konsentrasies Ca as blaarbespuiting of grondtoediening gemaak is. Geen parameters gemeet; knol varsgewig, knolgetal, soortlike gewig, persentasie droë gewig of chemiese samestelling is statisties beïnvloed deur óf die blaartoediening of grondtoediening nie. Dit blyk dat Ca blaarspuite teen hierdie dosis en tyd van plant ontwikkeling geen bykomende voordeel het op opbrengs of kwaliteit aspekte van moere nie.

Kalsium bemesting kan 'n positiewe effek hê op die opbrengs en kwaliteit van aartappel knolle maar die toedieningspeile en metode van toediening is uiters belangrik. Kultivars reageer ook verskillend op Ca bemesting, 'n aspek waarvan produsente deeglik moet bewus wees.

Contents

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The potato (*Solanum tuberosum L.*) is an annual herbaceous crop that originated in the Andes from high altitude tropical areas and grows up to 100 cm tall, producing tubers rich in starch. The potato belongs to the *Solanaceae* family and is divided into two cultivar groups: Andigenum is adapted to short day conditions and Chilotanum, adapted to long day conditions (FAO 2008). The potato is the world's most significant root and tuber crop globally and rates fourth among the world's agricultural products in terms of production volume, after wheat, rice and corn (Fabeiro et al. 2001). The potato is a temperate crop, growing and producing well in cool and humid climates. However, it is grown in more than 125 countries and consumed almost regularly by more than a billion people (FAO 2008).

One African country that plays an important role in the export of potatoes is Egypt, which is ranked 5th in world markets (FAO 2011). Potatoes are produced in 16 geographic production areas in South Africa (Theron 2003), as indicated in Figure 1. According to Potato South Africa (2015), based on the production of potatoes in 16 regions in South Africa, 53 933 hectares potatoes were planted in 2015, which produced 116 433 655, 10 kg bags. Ewing (1997) found that under ideal conditions the fresh mass of potato tubers can reach at least 100 t ha^{-1}. According to Potatoes South Africa (PSA 2012), there were 654 production units for potatoes in 2011. Since the early 1990's the area under potato production has gradually declined, while the average yields have steadily increased to the current average of more than 40 t ha^{-1} (PSA 2015).

It is estimated that production of table potatoes comes from between 700 and 800 commercial producers, who produce the total South African crop of seed and table potatoes (PSA 2012). During 2012, approximately 106 million x 10-kg pockets of potatoes were sold on the major fresh produce markets, compared to 101 million in 2011, an increase of 5,0%. The Johannesburg fresh produce market remained the biggest outlet, followed by the Tshwane, Cape Town and Durban markets. During the 5 years from 2008 to 2012, potato sales on the major fresh produce markets on average showed an increase of approximately 2,9% per annum (Department of Agriculture and Food 2015). Based on consumption of potatoes, the world is facing a shift in consumers demanding for more processed products than fresh potatoes, particularly in the developed countries. The rest are used for the processing industry, as cattle feed, processed into starch for industrial use and used as potato seed for the following seasons' planting (FAO 2008).

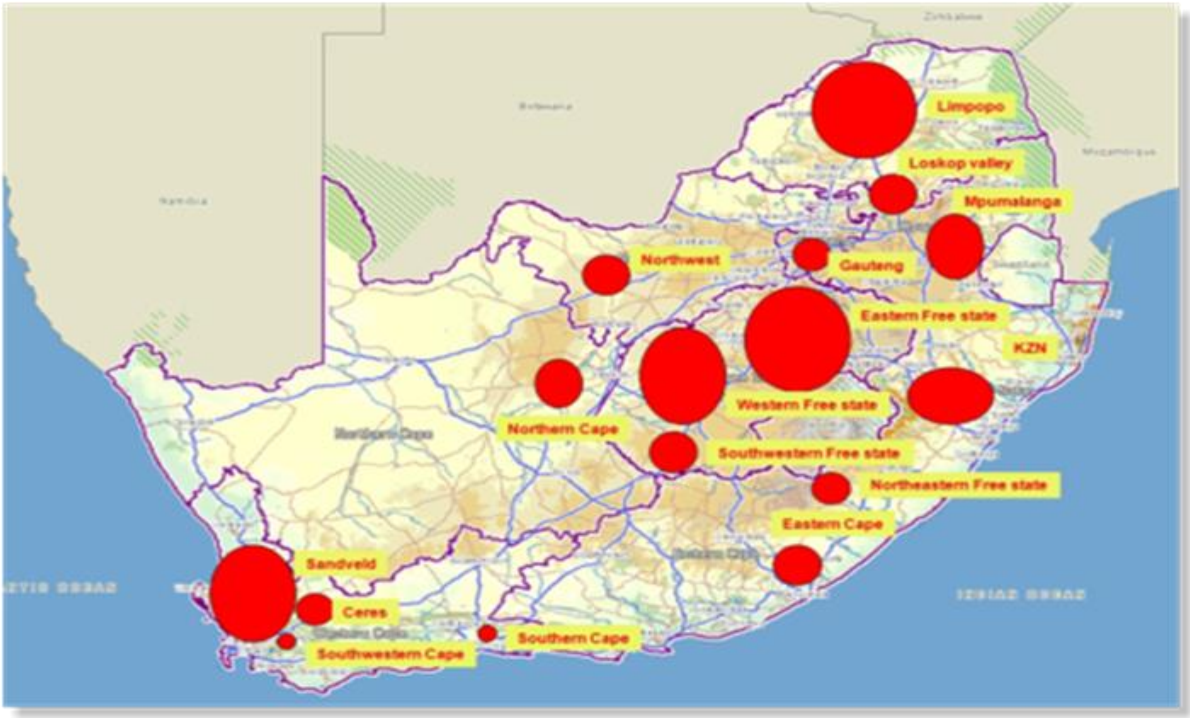


Figure 1: Potato producing areas in South Africa. Oval sizes represent the relative area of each potato producing region. (Image author: Mark du Plessis, Source: Potato South Africa).

POTATO CULTIVARS

Coleman (2015) reported that the main cultivars that are being grown and produced by local producers in South Africa are Mondial at 38%, Sifra at 19.45% and Valor third at 4.46%. Potatoes cultivated in the Sandveld are all under irrigation. The main varieties for table potatoes (Mondial 25%, BP1 23% and Avalanche 20%) were planted for summer crop and for winter crop (Mondial 26%, Sifra 20% and Avalanche 12%) (PSA 2014). According to Farmers Weekly (2015), Mondial is popular due to its high yield and excellent scab resistance.

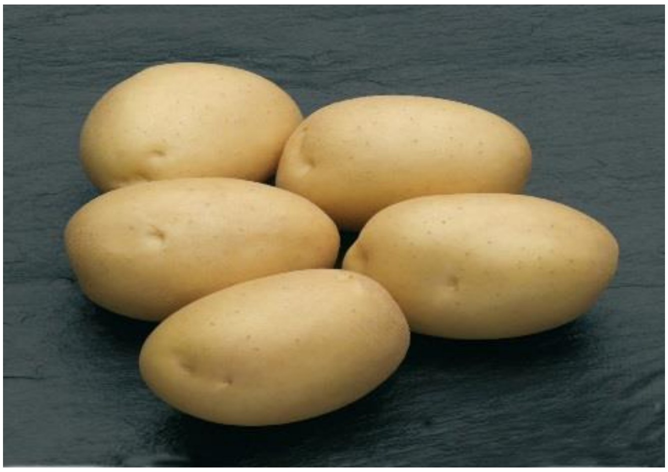
Lanorma

According to the website of the national seed potato marketing channel for South Africa (Aartappel Netwerk Suid Afrika (ANSA) 2008), Lanorma originates from the Netherlands. Plants are strong and grow very fast to medium to tall plants with high foliage. Lanorma only grows 80-90 days from emergence till natural foliage die off. Tubers have a bright clean yellow skin colour and a bright pale yellow flesh colour. The tubers are large, with a round oval shape, shallow eyes, and are relatively uniform in size. A low percentage of small tubers are produced. Lanorma produces high yields under favourable conditions and mature at the mid-season. This cultivar is tolerant to environmental extremes and suitable for dry land conditions because it can adapt to high temperatures and drought conditions. According to Real Potatoes (2014), Lanorma is resistant to mechanical damage, internal bruising, the development of hollow heart, growth cracks, and second growth, and also foliar and soil borne diseases. The plants are however slightly susceptible to late blight (*Phytophthora infestans*) on leaves as well as on tubers.

Mondial

Mondial is a cultivar that has oval shaped tubers with a pale yellow skin and flesh. This cultivar also originates from the Netherlands. The growth period is 90-110 days from emergence until natural foliage death. Mondial produces high yields in spring, summer and winter plantings. The tuber size distribution is predominantly medium to large tubers and tubers appear to be more uniform under optimal conditions. A large amount of mis-formed tubers can result when heat and water strain is experienced during tuber development. It was reported that the internal quality of the tubers deteriorates within 45 days after the natural death of foliage. The storability will be significantly reduced when the plants experience heat or water stress during the growth periods, also resulting in both internal browning and hollow hart. Mondial is very susceptible to early blight (*Alternaria solani*) and fusarium wilt (*Fusarium oxysporum*) (ANSA 2008; Potatoes South Australia 2016).

Sifra



Sifra produces a round oval shaped tuber with white smooth skin, early skin set and creamy flesh (HZPC 2013). The Canadian Food Inspection Agency (2016) reported that Sifra originated from a cross between Mondial and Robinta, made at HZPC Research in Metslawier, Netherlands. Sifra is a vigorous grower and is late maturing, thus the nitrogen application level should be maintained to ensure the foliage is sustained throughout the season. Sifra has a moderate resistance to foliage blight and a robust blight control programme is therefore recommended. It has an upright growth habit and an intermediate type foliage structure. Due to the bruising susceptibility of Sifra, it is recommended to apply high rates of potassium (K). Soils with a high availability of K may also help to reduce bruising at harvest.

Innovator

This cultivar originated from Netherlands. It has yellowish green leaves and a white corolla flower. Innovator is an early to mid-season cultivar producing tubers with a tan russet skin and light yellow flesh. Innovator is a high yielding cultivar that produces long oval tubers with a uniform tuber size distribution, a medium to high dry matter content and good storability. It is resistant to pale cyst nematode, internal bruising and moderately resistant to common scab and leaf roll (HZPC 2013; EPG 2015).

DEVELOPMENTAL STAGES OF POTATO GROWTH

Potato growth is classified into four distinct growth phases namely sprout development, tuber initiation, tuber bulking and tuber maturation (Struik and Wiersema 1999). The duration of these growth phases are determined by the environmental and management factors between locations as well as the cultivars. Each of these growth stages can be even further separated into early, mid and late categories and are similar to those proposed by van Loon (1981). One advantage of this classification system is that plant development is measured by physiological criteria. This provides a universal comparison between potato growing areas with differing growing seasons.

Sprouting and plant establishment

Sprouts develop from the eyes of the seed tuber which begins after the dormant period, and this period differs depending on the cultivar and storage temperature. Initially, only one sprout is formed and more sprouts are formed as the apical dominance of the growing point decreases (Krijthe 1962; Frazier et al. 2004; Johnson 2008). According to Frazier et al. (2004), sprout development is associated with the conversion of starch to sugars. Formation of sprouts is normally influenced by the physiological age of the seed tuber (Struik and Wiersema 1999). Mikitzel and Knowles (1989) found that strong sprouts develop from young potato seed tubers while sprouts with low vigour were produced by tubers of advanced physiological age. Leaves and branches develop from aboveground nodes along with the emerged sprouts, while the roots and stolons develop from or below the ground nodes (Johnson 2008). Axillary shoots develop from the main axis (Taylor 1953). The study by Ewing and Wareing (1978) found that day length (minimum of 6 short days) reduced the shoot growth at the upper bud and increased the underground stolon growth. Clarke and Lombard (1942) found that potato cultivars differed in the number of mature flowers they produced. The shoot system of potato is the combination of stems with terminal inflorescences. Stem development is expressed as the leaf and flower primordia production per stem (Almekinders and Struik 1996). Clarke and Lombard (1942) found that immature buds that develop in the first potato inflorescence are influenced by the variety and size of the seed piece. Flower primordia and flowering transition is affected by temperature and photoperiod (Almekinders and Struik 1996; Navarro et al. 2011).

Tuber Initiation

This stage begins when the potato tubers develop at the tips of the stolon, while they're not enlarging (Ojala et al. 1990). According to Mihovilovich et al. (2014), the tuber initiation phase occurs at about 20 to 30 days or more (up to 45 days under long day conditions) after plant emergence. It however differs between cultivars and depends on environmental conditions. Cowan (1986) reported that the tuber initiation stage is very short and takes only 10-15 days. Ewing and Struik (1992) stated that tubers can develop on other parts of the plant above ground, usually from the axillary nodes on the stem. This is known as arial tubers. Long days have been shown to suppress tuber initiation of potatoes (Steward et al. 1981), although the results varied between cultivars. Environmental and fertilisation factors control tuber initiation in potato plants, through their effect on the levels of endogenous growth substances (Wareing and Jennings 1979). Tubers with the highest mass are said to be produced by the lowest stolon on the main tubers (Clark 1921). Menzel (1980) and Sattelmacher and Marschner (1978) reported that short days and cool night temperatures plays a significant role in promoting tuber formation whereas long days, high night temperatures, and high nitrogen fertilisation inhibit or delay the process of tuber formation. At temperatures lower than 15^{o}C, tuberization is delayed by one week and at temperatures higher than 25^{o}C, tuberization is delayed by three weeks (Levy and Veilleux 2007). Nitrogen absorption rate increases gradually during tuber initiation (Ojala et al. 1990). There are numerous factors that affect tuber formation including nitrogen levels, temperature, light levels and also bacteria in the root-sphere (Kempen 2012). Adequate nitrogen availability stimulates vine growth and may delay the tuber initiation phase up to ten days (Kleinkopf et al. 1981). According to Mihovilovich et al. (2014), during the tuber initiation phase where tubers are formed on stolons, the orientation of cell division within the sub-apical portion of the stolon changes to produce radial expansion rather than longitudinal growth. Kleinkopf et al. (1981) found that nitrogen uptake rate increased slightly during tuber initiation.

Tuber bulking

According to the International Potato Center (CIP 2014) tuber bulking has a duration of 60 to over 120 days, depending on length of growing season and presence of pathogens. Tubers differ in shape and size, generally they weigh up to 300g each (FAO 2008). In the upper surface, they have more hollows called eyes, which contain auxiliary buds which are spirally organised around the tuber. The rate and duration of tuber bulking determines the yield in potato crops. The tuber bulking stage is characterised by a constant rate of increase in tuber size and mass, unless there's a presence of a limiting factor (Ojala et al. 1990). Tuber bulking rate is increased by short photoperiods, high light intensity and cool climates (average daily temperatures from 15° to 18°C). Heat, soil temperatures and water stress are the major environmental factors that limit the tuber bulking, and thus indirectly affect potato production. Crop senescence is affected by high temperatures; temperatures higher than 30^{o}C shortens crop senescence (Mihovilovich et al. 2014). Heat stress results in a higher number of smaller tubers per plant and lower specific gravity with a reduced dry matter content of tubers (Haverkort 1990). During the tuber bulking stage, there's an accumulation of water, carbohydrates and nutrients due to the expansion of cells. Tubers become the reservoir for deposition of carbohydrates and mobile inorganic nutrients (Cowan 1986). The tuber bulking rate can be described by the slope of a linear curve, with the increase in tuber mass over time, while tuber bulking duration is the time between tuber initiation and persistence of foliage (Ojala et al. 1990). During this stage, the vast majority of nutrients are taken up and nitrogen fertigation is critical (Cowan 1986). Inadequate nitrogen reduces tuber yield and size due to a lower tuber bulking rate (Ojala et al. 1990), nevertheless, excessive nitrogen decreases tuber specific gravity and delays vine senescence, which usually promotes tuber immaturity.

Tuber maturation

This stage begins with canopy senescence. The growth rate of the tuber is lower during maturation than during the tuber bulking stage (Ojala et al. 1990). During maturation, the growth rate of the tubers slow down, photosynthesis decreases and vines die back (Kempen 2012). Increases in tuber dry matter result largely from translocation of photosynthates from the tops and roots into the tubers (Ojala et al. 1990). As tubers reach the maturing stage the buds become successively dormant (Braue et al. 1983). Larsen (1984) stated that potato plants require supplemental water for tuber bulking during maturation due to very low evapotranspiration rates from soils and senescing vines. Water stress during maturation plays a vital role in improving the post-harvest tuber resistance to water loss (Braue et al. 1983). Ojala et al. (1990) found that high nitrogen availability during the entire growing season, particularly late tuber bulking, normally delays tuber maturity.

POTATO FERTILISATION

The use of soluble fertilisers for crop production, particularly to supply nitrogen (N), phosphorus (P), and potassium (K), has increased potato yields and quality for several decades (Davenport et al. 2005). A number of studies has been done on fertilisation of potatoes, and one of them by Imas and Bansal (1999), has shown that the potato crop has strict requirements for fertilisation management, without which growth and development of the crop will be poor, resulting in lower yields and poor quality tubers. Potato growth depends on the supply of nutrients, such as nitrogen (N), phosphorus (P) and potassium (K) and the application of fertiliser depends on the level of available soil nutrients. Gupta and Saxena (1976) reported that increasing the application rates of nutrients increases the yield to a certain level beyond which further application will decrease the yield. Phosphorus (P) along with potassium (K) and nitrogen (N) are classified as primary macronutrients (Marschner 1995).

Nitrogen

Matson et al. (2002) reported that N is an essential plant nutrient, with a considerable effect on potato production, which plays a vital role in improving plant yield and quality. Adequate pre-plant N fertilisation can delay potato tuber growth, 7 to 10 days after planting, particularly for indeterminate potato varieties (Kleinkopf et al. 1981). However, Inthapanya et al. (2000) found that the nitrogen utilization rate differs significantly among different cultivars. According to Moorby (1978), N has a significant influence on the production and maintenance of plant foliage, which indirectly relates to optimum tuber growth through long growing seasons. During peak periods of tuber formation, nutrient requirements may exceed the uptake rates and cause a deficit of phloem mobile nutrients from the tops to the tubers. If deficiencies occur early in the growing season, premature canopy senescence may be encountered (Dyson 1965; Harris 1978), which may indirectly result in reduced tuber yields.

Plants take up N as both nitrate (NO_3^-) and as a monovalent cation, ammonium (NH_4^+), but crops tend to grow better when they get the majority of their N as NO_3^-. Ammonium first needs to be metabolised because it can be toxic within the cells (Barker and Pilbeam 2007). Ammonium can also inhibit the absorption of NO_3^- (Breter and Siegerist 1984). Plants with nitrogen deficiencies have yellow leaves due to the decrease in synthesis of proteins and chlorophyll (Olfs et al. 2005).

Nitrogen plays a significant role in enhancing leaf and tuber growth and providing high yields but over-use of N early in the growing season can lead to excessive vegetative growth during tuber formation. Providing crops with adequate N to develop and maintain a large leaf area enables maximum light interception to occur. About 58% and 71% of the total nitrogen absorbed by roots occurs through early and mid-tuber bulking, respectively (Westermann and Kleinkopf 1985).

Phosphorus

Phosphorus (P) is an essential plant nutrient that provides energy for plant processes such as ion uptake and transport and plays an important role in early root and shoot development (Marschner 1995). According to the study conducted by Maier et al. (1989), phosphorus application significantly increases the total tuber yield. Gregory (1988) stated that the early growth of a potato plant is characterized by limited root development and a poor capacity of roots to deplete soil nutrient reserves. Phosphate (P) fertilisation can increase early leaf development, tuber set, tuber yield and tuber quality (Rowe 1993; Marschner 1995; Jenkins and Ali 2000). Plants absorb phosphorus as $H_2PO_4^-$ or HPO_4^-. Schachtman et al. (1998) reported that inorganic phosphate (Pi) enters the root system through co-transport with positively charged ions and the cytoplasmic acidification which is in relation with P uptake indicates that the cation is H^+. However, even though some soils contain large amounts of P, only a small proportion is available to plants. Shen et al. (2011) found that one unique characteristic of P is its low availability because of slow diffusion and high fixation in soils, which means that P can be a limiting factor for plant growth. George et al. (2008) reported that intensive use of P-fertilisers has resulted in the accumulation of P in soils, in forms that are poorly available to plants. During early growth stages, plants are unable to access enough P (Ai et al 2009). According to Rodriguez (1993) the potato has a low root density and requires large amounts of phosphate fertiliser; from 60 to 80 kg ha^{-1} P, to reach economically acceptable yields. Increasing nutrient availability in the soil solution results in an increase in the crop yields as a result of an increase in size of the photosynthetic apparatus (McCollum 1978a, 1978b).

Potassium

Potassium (K) is an essential macro nutrient for all plants and is the most abundant essential cation in plant cells (Wang and Wu 2013). Potassium plays a vital role in determining yield and quality of potatoes, as well as the vigour of the crop (Panique et al. 1997; PDA 2007). The potato plant has a relatively high K requirement in order to achieve tuber yields (Westermann et al. 1994). Potassium also has a positive effect on root development and growth and therefore K application at planting is generally needed (Roberts and McDole 1985). Potassium has a major role in the transportation of sugars and synthesis of starches in potatoes (Harris

1978). The presence of chloride (Cl) in the soil solution affects the absorption of K and it also increases the translocation rate of K in corn roots (Kochian et al. 1985). This is supported by Barker and Pilbeam (2007), since they found that potatoes are able to sense the availability of K^+ in roots and plant membranes are selectively permeable to K^+ as a result of various K^+ channels in the plasma membrane. Potassium affects the water composition of the plasma volume, therefore affecting the water content of fleshy storage chambers, e.g. the tubers (Bergmann 1992). Potassium deficiency symptoms result in a reduced plant height, reduced shoot and leaf growth and leaf colour that is commonly dark green with a bluish tinge (Trehan et al. 2001) as well as poor potato yields and reduced tuber sizes (McDole et al. 1978). The foliage wilts and dies as the deficiency progresses and tubers starts to develop black spot.

Calcium

Potato tubers have minute levels of endogenous calcium (Ca) compared to other vegetative parts (Simmons and Kelling 1987). According to Sterrett et al. (1991), tuber yield is not affected by soil applied Ca, El-Beltagy et al. (2000) found that tuber yield increase with an increase in Ca to medium levels. Calcium related physiological disorders are affected by several features such as Ca uptake and poor water transport to organs with a low transpiration rate (Kempen 2012). Physiological disorders such as hollow heart and internal brown spot severely affects potato tuber quality and may be associated with the Ca content of tubers. The post-harvest susceptibility of tubers to soft rot pathogens has also been found to be related to the tuber Ca composition (Locascio et al. 1991).

Calcium is one of the essential plant nutrients and performs a significant role in plant membrane structure and function where it contributes to maintenance of cell membrane stability and wall structure (Marschner 1995). Calcium therefore increases plant tissue resistance against biotic and abiotic stress (Ilyama et al. 1994). Palta (1996) reported that the ability of Ca to bond phosphate and carboxylate groups of phospholipids at the membrane surface helps increase cell membrane stability. Marschner (1995) reported that crops receiving large amounts of Ca during growth contain high levels of pectic materials such as calcium pectate. Harris (1992) confirms that Ca also assists plants to adapt to stress by inducing the signal chain when stress occurs; it has a key role in regulating the active transport of K for stomatal opening, and is particularly significant in helping summer heat stress, thus lowering wilting. Calcium also promotes root development and growth of the plant as it is involved in root elongation and cell division (Ilyama et al. 1994). In a study conducted by Clarkson (1984) it was shown that there are reduced incidences of internal rust spot and necrosis. According to Harris (1992) high levels of Ca in the tuber lowers the bruising risks at harvest and subsequent transportation.

Importance of calcium in potatoes

Calcium plays a significant role in tuber quality by forming part of the membrane cell wall structures (Kleinhenz and Palta 2002). Palta (1996) reported that the current evidence indicates that potato tuber quality can be enhanced by increasing the Ca content of the tubers. Supplementary Ca in the rhizosphere can increase the Ca concentration of the tubers and result in improved quality (Kratzke and Palta 1985). Benefits from supplemental Ca application include reduced incidence of interior defects such as internal brown spot (IBS) and hollow heart (HH) (Palta 1996). Schöber and Vermeulen (1999) reported that Ca increased resistance of witloof to soft-rot pathogens, however high applications of N increased incidence of the same soft rot pathogens. The experiment that was conducted by Rhue et al. (1986) showed that application of Ca on coarse textured soils containing 250 to 350 mg extractable Ca kg^{-1} soil have consistently resulted in increased yields and increased tuber quality, however Dubey et al. (2013) found that responses were unreliable with Ca applications on soils with higher Ca concentrations.

Calcium uptake and distribution

Calcium occurs as a relatively large cation which freely enters the apoplast and is bound in exchangeable form in cell walls and outside the plasmalemma. Calcium moves in an apoplastic manner because it is related to water movement (Kirkby and Pilbeam 1984). Ions in the rhizosphere are shifted to the roots by mass flow or diffusion, the occurrence of this phenomenon depends on the ion concentration of the soil solution (Bangerth 1979). According to Kleinhenz and Palta (2002) potato tubers have a low Ca composition due to poor Ca uptake and the inadequacy of Ca distribution between the vegetative and storage organs. However Karlsson and Palta (2002) stated that applying Ca to the soil solution close to the stolons and tubers is the best way to improve tuber Ca content. Westermann and Davis (1992) reported that improving Ca tuber content can be attained through application of $Ca(NO_3)_2$ at tuber initiation stage via top-dressing. Calcium is relatively immobile in the plant and it cannot be translocated from the leaves to the tubers. The distribution of Ca in the potato plant is quite uneven, with shoots containing 1.5 % per dry mass and tubers only 0.05 – 0.15 % per dry mass (Kempen 2012). In work done by Kratzke and Palta (1985) it was found that the low Ca composition of tubers is the result of limited Ca transport through the transpiration stream, limited transport of Ca in the xylem and its immobility in the phloem. Kempen (2012) reported that there's an unevenly distribution of Ca with higher concentrations present in the exterior periderm of the tuber compared to the pith.

Interchange adsorption on the xylem surface, results in the low Ca composition of the tubers. The low Ca content of the tubers may be magnified when potatoes are grown in sandy soil with low cation exchange capacity and low soil Ca content (Tzeng et al. 1986).

Calcium deficiency, physiological disorders and resistance to stress

On arable soils, crops rarely show symptoms of Ca deficiencies because Ca is one of the most abundant cations in soil solutions (Seling et al. 2000). Calcium deficient plants are spindly with small, upward rolling, crinkled leaflets having chlorotic margins, which then result in necrotic lesions forming. Naturally, the symptoms of a Ca deficit, in addition to growth reduction, also involve browning phenomena and necrosis of whole areas of plant tissue (Hooker 1981; Seling et al. 2000). These deficiencies result in low yields and poor quality of potato tubers. Hooker (1981) stated that seed tubers in soils with Ca deficiencies remain hard and produce relatively normal roots. According to Modisane (2007), Ca insufficiency in potato tubers is not only due to inadequate Ca uptake by the potato plant, but also as a result of problems related to Ca distribution within the plant which results in Ca related disorders.

Calcium deficiency symptoms are more severe in potatoes grown in sandy soils (Hooker 1981). Calcium deficiencies are associated with many physiological disorders such as internal brown spot (IBS) and hollow heart (HH). These disorders are normally called tissue necrosis (Sterrett et al. 1991). In many cases, it is not easy to distinguish between internal heat necrosis (IHN) and IBS (Yencho et al. 2008). Baruzzini et al. (1989) reported that IHN of potato tubers can be distinguished by reddish-brown flecks in patches of tuber parenchyma tissue. At the microscopic level, affected cells have thickened cell walls. Lower tuber Ca content is related with increased susceptibility to bacterial soft rot and IBS (Rhue et al. 1986), which occur in the intercellular spaces and also in the vascular tissue where they normally affect the transport mechanism (Baruzzini et al. 1989). A high incidence of IBS reduces potato tuber quality and its market value (Sterrett et al. 1991). According to Karlsson and Palta (2002), Ca has an important role in tuber storage quality and physiological health/tuber health. Kratzke and Palta (1985) reported that the onset of IBS can be overcome by applying additional Ca to potato crops. Results of trials by Palta (1996) indicate that benefits from additional Ca application include reduced incidence of internal defects such as IBS and HH (Figure 2). The environmental factors such as temperature and humidity affect Ca uptake and distribution, thus this result in the IBS manifestation (Olsen et al. 1996), which leads to reduced potato production and poor quality of potato tubers.

Figure 2. Photograph showing a visual physiological disorder namely hollow heart.

FACTORS AFFECTING POTATO PRODUCTION

Water supply

There are many environmental aspects that affect yield of which water supply is a major limiting factor in the production and quality of potatoes. Water deficiency affects potato production, since the crop is sensitive to water deficit, due to their deep root system (Harris 1978). The negative effect of water stress on tuber yield is partly due to a reduction of potential tuber production per day (Van Loon 1981). Epstein and Grant (1973) reported that water stress leads to closure of stomata which decreases the rate of transpiration and photosynthesis in potato plants. Van Loon (1981) found that there were varietal differences in resistance or tolerance to water stress. Roztropowicz et al. (1978) reported on the effect of water deficiency on six varieties. The most drought tolerant cultivar yielded without irrigation. Under optimal water supply 85% of yield was obtained and the least tolerant cultivar only produced 71%. Foti (1999) reported that potatoes grown for early production were sensitive to water stress, which adversely affected not only tuber yield but also time of tuber maturity. Levy et al. (2013) found that drought had critical effects on potato growth and yield, thus application of water is essential to obtain high quality tubers. According to Opena and Porter (1999) about 85% of the root length grows in the top 0.3 - 0.4 m of the soil, necessitating frequent irrigation. Schapendonk et al. (1989) reported that in order to achieve high production, soil water composition must be not less than 50% of total available water in the soil rhizosphere, particularly throughout the period of tuber formation.

Temperature

Potato plant growth, yield and development are also severely affected by heat stress (Kleinhenz and Palta 2002). Management of heat stress in potato production is very important when it is grown under warmer conditions (Kumar et al. 2005).

The potato is grown under many different environmental conditions, but it really requires moderate climatic conditions (Haverkort 1990). Stol et al. (1991) reported that under high temperatures, above 17°C, the tuber formation rate is lowered (Reynolds and Ewing 1989). Hijmans et al. (2003) found that the potato crop is sensitive to frost and can be critically damaged if subjected to temperatures below 0°C. Lafta and Lorenzon (1995) reported that good tuber formation is dependent on temperatures between 15°C and 20°C and it is inhibited when the temperature increase to 30°C or drops to 10°C. According to the FAO (2008), tuber growth is drastically inhibited at temperatures below 10°C and above 30°C while optimum yields are obtained where average temperatures are in a range of 18 to 20°C. According to Hijmans et al. (2003), depending on the temperature regime and the crop, high temperatures result in low yields due to increased development rates and higher respiration. Photoperiod and temperature affect the degree of crop growth and development and temperature also plays a role in determining the duration of different growth stages of the potato crop (Lafta and Lorenzen 1995).

Fertiliser application methods and rates

According to Hawkins (1954), the potato crop is one of the most responsive crops to fertilisation. The significant factors that should be considered when dealing with applying fertilisers are the optimum amount of nutrients to obtain desired yields and quality (Bailey 1927), the correct time of application, the method of application, and the application rates (Brown et al. 1939). There are various methods of applying fertiliser in potato production, such as band placement, broadcasting of fertilisers (Dahnke et al. 1989) and split application (Davis et al. 2009). Davis et al. (2009) stated that growers should know the requirements and characteristics of a certain crop before applying early season N fertiliser.. Other studies reported that maximum yields were obtained with row fertiliser application compared to broadcasting (Jordan and Sirrine 1910; Cooper and Rapp 1926, Bailey 1927). Band placing the fertiliser in rows, reduces phosphate fixation and provide readily availability of nutrients in close proximity to the developing seedlings (Hawkins 1954; MacLean 1984).

Split application of N fertiliser involves applying N fertiliser at pre-plant or at planting, with the remainder which can be applied through fertigation (Davis et al. 2009). This results in an increase in N use efficiency and lower leaching by reducing the excess availability of N in the soil solution (Victory 1999). In a study by Westermann et al. (1988), it was found that N use efficiencies were approximately 60% and 80% when applied pre-plant and during tuber growth, respectively. Westermann and Davis (1992) reported that fertigation was an accepted fertilisation practice, especially with sprinkler irrigation systems. Kunkel et al. (1977) found that adequate availability of N at planting could increase salt levels, which indirectly influence the availability of moisture in the root zone. Zeng et al. (2013) found that split applications of fertiliser resulted in good fertiliser use efficiency by allowing the timing of applications to better correspond to patterns of plant nutrient requirement. Davis et al. (2009) found that N fertiliser requirement by potatoes were best met by split applications of N fertilisers during the vegetative stage. According to Perrenoud (1983), a potato crop yielding 37 t ha^{-1} removes 113 kg N, 45 kg P_2O_5 and 196 kg K_2O per hectare. According to a report by the Kwa-Zulu Natal Department of Agriculture (2005), potatoes require NPK fertiliser, at a rate of 7 kg ha^{-1} N, 10 kg ha^{-1} P, 13 kg ha^{-1} K respectively.

QUALITY PARAMETERS OF POTATO TUBERS.

Specific Gravity

Specific gravity (SG) of potatoes is is a major criterion for processing and plays a significant role in measuring the quality of potato tubers (Myhre 1959; Lulai and Orr 1979; Davenport 2000; Geremew et al. 2007). Specific gravity plays an important role in estimating the dry matter content of potato tubers and also in reflecting the environmental factors during the growing season (Geremew et al. 2007; Abebe et al. 2013). According to Geremew et al. (2007), SG indicates the maturation of the tuber. Specific gravity of individual potato tubers varies within each cultivar and between cultivars (Wright et al. 2005). There's a good relationship between black spot bruise susceptibility and tuber-specific gravity (Smittle et al. 1974). Storey and Davies (1992) found that potatoes with a high SG were generally more susceptible to bruising than those with a low SG. Wright et al. (2005) found that as the tuber SG increased, the severity of bacterial soft rot decreased, and the severity of bruising increased. Specific gravity is extensively used by the potato industry to evaluate the baking characteristics, and storability of potatoes and also to assess the suitability of tubers (Geremew et al. 2007; Abebe et al. 2013). When potato tubers have low specific gravity, they are used for canning and boiling (USDA 1955). Terman (1950) reported that intensive fertilisation, especially with nitrogen or potash fertilisers, normally results in tubers with low specific gravity. According to previous studies, average specific gravity ranges from less than 1.060 to greater than 1.089. Specific gravity between 1.060-1.069 is regarded as low and 1.080-1.089 as high (Mosley and Chase 1993; Abebe et al. 2013). It has been recommended that in order to yield potatoes with high SG, ideal agronomic practices should be considered, such as planting high quality seed of the correct variety at the right time of the year, applying N and K fertiliser to meet crop needs and good Irrigation management (Department of Agriculture and Food 2015).

Internal defects

There are numerous internal defects that affect tuber quality. One of the most prominent, hollow heart, manifests as an irregular hole at the centre of the potato. It is caused by among other factors, excessively rapid growth. Improper field or storage conditions, freezing or disease may also cause defects, which are normally characterised by internal discoloration (USDA 1975). According to van Denburgh et al. (1980), the value of processing potatoes is normally affected by internal defects such as brown center and hollow heart, which results in poor quality. In contrast, Hiller and Koller (1984) found that in spite of the fact that brown centre and hollow heart is related, the problem can occur independently of each other. Brown centre and hollow heart are characterised by the discoloration that arises from the damaged cell membranes and organelles, and necrosis of affected cells (US Department of Agriculture 1975; van Denburgh et al. 1980). The study by Hiller and Koller (1982) showed that high soil water contents during tuber initiation increased the incidence of brown centre.

Keeping quality during storage

The way potatoes are stored depends on the cultural expectations for the quality of tubers coming out of storage, the desired duration of the storage period and local environmental conditions (Bethke 2014). Eltawil et al. (2006) stated that the main aim of storage is to maintain tubers in their most edible and marketable condition. Rastovski (1987) concluded that average storage temperature should be 5^{o}C for a period of 6 months, 10^{o}C for 3-4 months. There are different methods used to store tubers, and the period it takes during storage indicates different climatic conditions and target markets (Bethke 2014). The most significant factors that should be considered during storage are temperature, humidity, CO_2 and air movement (Harbenburg et al. 1986; Maldegem 1999). The storage methods include ground storage, whereby mature potatoes are left in the ground for an extended period, without being harvested (Bethke 2014). However, Verma et al. (1974) stated that storage of potatoes at ambient room temperature during hot temperatures results in severe mass and quality loss. Bethke (2014) stated that potatoes in storage may develop quality defects that adversely decrease the value of the crops in storage. The quality of potato, and its storage life, is reduced by the loss of moisture, decay and physiological breakdown (Eltawil et al. 2006).

Sprouting capacity

According to Frazier et al. (2004), effective sprout control is a major component of managing stored potato quality. Briddon (2006) reported that an absence of sprouts in potato tubers is an important visual indicator of quality. Tuber quality is negatively influenced during storage by sprouting, and this result to reduction in tuber quality. Sprouting causes mass loss during storage. If proper sprout is not maintained, significant reduction to tuber quality normally occurs (Frazier et al. 2004). Frazier et al. (2004) reported that sprouting may inhibit airflow through the potato pile, reduced airflow normally leads to increased pile temperatures and an increase in disease problems which negatively affect tuber quality. Briddon (2006) found that an increase in reducing sugar levels can be adequate to have a considerable, deleterious effect on processing quality.

Most potato varieties are dormant for more than three weeks (Shibairo et al. 2006). According to Aksenova et al. (2013), this is due to unfavourable environmental conditions, stage of tuber development and storage. However, Muchiri et al. (2015) reported that dormant potato seed tubers can be induced to sprouting by treating with cytokinins and gibberellins (GA). Factors that negatively affect sprouting capacity includes high levels of ethylene and diffused light (Demo et al. 2004; Shibairo et al. 2006). Hdiberg (1970) reported that it is important to terminate dormancy in freshly harvested potatoes to enable the potatoes to sprout for enhancement of early planting and increased potato productivity.

PROBLEM STATEMENT

Calcium is often deficient, specifically in slow transpiring organs such as fruit and tubers resulting in localised deficiencies that may cause physiological disorders (Simmons and Kelling 1987). Potato tubers, being underground storage organs, have especially low levels of Ca due to the limited Ca transport in the xylem, their low transpiration rate and the immobility of Ca in the phloem. This results in most of the Ca that is taken up being translocated to the shoots. Kempen (2012) stated that the distribution of Ca in the potato plant is uneven with shoots containing as much as 1.5 % Ca per dry mass and the tuber on average only 0.05 – 0.15 % Ca per dry mass. This low Ca content of tubers has been linked to many disorders in potatoes. Modisane (2007) found that a high incidence of IBS resulted in reduced tuber quality and market value of potato crop. Davies (1998) reported that low levels of Ca may also play a role in internal defect and IBS occurrence. Cultivars are also expected to vary with regards to their ability to take up Ca and their susceptibility to internal defects and environmental conditions will also play a role. This study seeks to identify a way of improving the Ca nutrition of commonly used potato cultivars to improve tuber quality, yield and reduce the incidence of physiological disorders.

The overall objective of this study was to determine the effect of different Ca application rates and methods on the growth, development, yield, tuber formation and tuber quality of potato cultivars. These objectives were obtained by:

1. Assessing the Ca concentration in tubers of four potato cultivars cultivated in pot trials under drip irrigation with different concentrations of Ca.

2. Determining the influence of Ca application rates under simulated field conditions on plants grown on three different soil types.

3. Determining the influence of foliar fertilisers on tuber quality, where $Ca(NO_3)_2$ was used as a source of Ca.

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CHAPTER 2

Effect of different calcium application levels on the quality, growth, development and yield of potato tubers.

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Abstract

Calcium (Ca) is one of the most abundant elements in soil and this element contributes to the maintenance of cell membrane stability and cell wall structure of plants. Recent studies have indicated that tissue Ca level is linked to the quality of horticultural products and in the case of potatoes (*Solanum tuberosum*), a reduction in tuber internal defects and an improvement in storability can be expected. The purpose of the present study was therefore to determine the influence of Ca application rates on the growth, yield, development, tuberization and tuber quality of potatoes. The experiment was conducted in a greenhouse at Stellenbosch University. Potato seedlings of four cultivars (Mondial, Sifra, Lanoma and Innovator) were transplanted to 20L bags containing silica sand. Plants were drip irrigated with a nutrient solution containing 4 different concentrations of Ca (1.6, 3.2, 6.6 and 9.8 meq L^{-1} Ca). Tuber mass, shoot fresh mass and shoot dry mass was affected by the Ca application levels and also differed between the cultivars. Applying 3.2 meq L^{-1} of Ca throughout the growing season significantly increased tuber yields, however, further increases in Ca levels (9.8 meq L^{-1}) did not have an additional positive effect. Mondial, a popular South African cultivar, performed best in terms of tuber yield. Application of 3.2 meq L^{-1} Ca through drip irrigation therefore was most beneficial to yield parameters (tuber yield, shoot fresh mass and harvest index) in the selected cultivars. Tubers from Mondial and Sifra had a good visual quality with 65 % and 66 % of the tubers rated good. The results indicate that yield and quality of potatoes will be affected by the Ca application level and that the cultivars vary with regards to their response to Ca application levels.

Key words: calcium, nutrient solution, potato, tuber quality, tuber yield

Introduction

Calcium (Ca) is an essential plant element and plays a significant role in the potato plant (*Solanum tuberosum L.*) by maintaining cell membrane and cell wall structure. This is due to the stable but reversible linkages between the polar head groups and in pectic acid fractions that form in the cell wall. Calcium also plays a vital role in maintaining the quality of other fruits and vegetables (Ilyama et al. 1994; Marschner 1995; Palta 1996). Calcium is a non-toxic mineral nutrient and plant cells can tolerate very high concentrations of extracellular Ca (Palta and LeeStadelmann 1983). It has been reported that the presence of Ca in the extracellular solution tends to increase the bonds between the cell wall and the outer face of the plasma membrane (Gomez-Lepe et al. 1979).

Calcium is also one of the most significant elements in soil (Kleinhenz and Palta 2002) and is absorbed by roots before being deposited to the xylem chambers. Calcium is transported from roots to the entire plant with water by a series of cation exchange reactions (Bell and Biddulph 1963). Stark and Westermann (2003) reported that Ca was usually available in sufficient amounts in calcareous and/or alkaline soils as well as in irrigation waters to supply plant demand. According to Jenkins and Mahmood (2003), Ca can be applied as Ca nitrate, Ca sulphate and Ca chloride. Kirkby and Pilbeam (1984), stated that Ca is a limiting factor in plant growth under field conditions because Ca is restricted to uptake via the root tips. Calcium uptake is also restricted as the root becomes progressively older since increased deposition of suberin lamellae prevents direct access to the endodermis plasmalemma from the apoplast (Moore et al. 2002). Nevertheless, Kirkby and Pilbeam (1984) stated that Ca is not normally remobilized from old to young tissues, even under Ca-stress conditions.

Wareing and Jennings (1979) stated that tuberization in potato plants is controlled by environmental and nutritional factors, which has an effect on the level of endogenous growth substances. According to EL-Beltagy et al. (2000), potatoes prefer a cool temperate climate with temperatures between 15 ^{o}C and 22 ^{o}C for optimum production and quality. Short days and cool night temperatures promote tuber formation whereas long days, high night temperatures (over 26 °C), and high nitrogen fertilisation delay or inhibit this process (Gregory 1954; Sattelmacher and Marschner 1978; Menzel 1980). In the literature, there’s no specific prescribed nitrogen rate that delays or inhibit the tuber formation process. Gregory (1954) found that tuber initiation occurred in short days over a wide range of day temperatures, but this process was inhibited at high night temperatures (over 26 °C). In long days, the temperature range for tuber formation was greatly restricted, with the necessity for lower night temperatures (10-17°C).

Temperature has an influence on the plants' Ca content because it affects the absorption and distribution of Ca within the crop (EL-Beltagy et al. 2000). Potato tubers have low levels of Ca due to the limited Ca transport in the xylem and the immobility of Ca in the phloem (Simmons and Kelling 1987). Kleinhenz (2000) stated that potato Ca content is not only affected by the amount of Ca applied, but environmental factors also play a role in Ca absorption by potato plants. A low tuber Ca content may result in necrotic cells in the medullary tissue, which is a physiological disorder of potatoes called internal brown spot (IBS) (Bain et al. 1996; Olsen et al. 1996). Internal Brown Spot is an internal physiological disorder of potato which is characterized by brownish red necrotic patches of parenchymal tissue that occur along and/or inside the vascular ring (Yencho et al. 2008). A study by Sterrett and Henninger (1991) has shown that high incidences of physiological disorders such as IBS results in poor tuber quality which leads to economic losses for potato growers. Brown center, characterized by a region of cell death in the pith of the tuber that results in brown tissue can also result due to low Ca concentrations in the tuber (Zotarelli et al. 2015). Tissue necrosis such as brown center and IBS has been associated with Ca deficiencies (Levitt 1942; Bangerth 1979; Collier et al. 1980). Recently, there has been an increased concern over the poor quality and low yield of potato tubers due to tissue necrosis which is caused by low Ca content, thus this study seeks to increase the Ca content of potatoes. The aim of this study is to determine the effect of different Ca application rates on the yield, tuber formation, tuber development, growth and tuber quality of potatoes.

Materials and Methods

Experimental site and crop details.

The experiment was conducted in a greenhouse at Welgevallen, the experimental farm of the University of Stellenbosch, 33°56'33.9"S 18°51'59.0"E. Potato seed tubers (G1/G2) of four cultivars (Mondial, Sifra, Lanoma and Innovator) were used in this study. Seedlings were made by removing the eye and 4 cm of tuber flesh below it and planting these in seedling trays filled with a seedling mix consisting of coco-peat, perlite and vermiculite (Plate 2.1). This ensured a more uniform plant growth compared to just planting sprouted tubers. The seedling trays were sterilized with chlorine. Seedlings were transplanted on the 29th of September 2015. Plantlets were drip irrigated with a standard nutrient solution, at an EC of 1.2 mS cm^{-1}. Seedlings were transferred to 20 L (30 cm diameter) grow bags containing silica sand in a greenhouse, 5 weeks after planting in trays. During the crop growth, after transplanting, a standard pest and disease management program for potatoes was applied. The trial was terminated on the 8th of December 2015.

Plate 2.1 Preparations of potato seedlings from sprouted seed tubers and growing seedlings in trays.

Treatments and experimental design.

The trial investigated the effect of four Ca application levels on four potato cultivars. It was laid out in a factorial design with each treatment combination repeated four times. The four potato cultivars used were Mondial, Lanorma, Sifra and Innovator. The nutrient solutions consisted of a control (6.6 meq L^{-1}), low Ca (1.6 meq L^{-1}), medium Ca (3.2 meq L^{-1}) and high Ca (9.8 meq L^{-1}) (Table 2.1). The EC in all the solutions was maintained at 1.5 mS cm^{-1} and the concentration of the anions and micro-nutrients in each remained constant. To be able to vary the Ca concentration it was however necessary to make slight adjustments to the concentrations of the other cations in the solution (Table 2.1). The variation in the concentrations of the other cations was still much smaller than that of Ca^{2+}. The nutrient solution was applied via drip irrigation and pots received 200 ml nutrient solution four times a day at 10:00, 12:00, 14:00 and 16:00.

Data collected

The effect of the different Ca applications on crop growth, yield and quality of potatoes was assessed after harvesting, 68 days after planting (DAP). At harvest, the plant was divided into shoots (leaves and stem), roots and tubers and the fresh mass of each was determined before all the plant parts were oven dried at 80°C for 4 days and the dry mass determined. Root/shoot ratio was calculated by dividing root mass by the shoot mass. Harvest index was determined by dividing the tuber biomass by total shoot mass plus tuber biomass. Harvested tubers were visually inspected for any defects before they were graded as small (<20g), medium (>20-80g) and large (>80g). The visual quality was determined by categorizing tubers based on the number of observations whether the tubers were defected or not. Tubers were considered not defected when no visual defects were visible, and tubers were considered defected when visual defects were visible (when tubers were affected by both IBS and other disorders and diseases as shown in Plate 2.2). The data did not have numbers, the data was descriptive qualitative thus descriptive statistics was used to analyse data.

A **B**

Plate 2.2 Potato tubers affected by Internal Brown Spot (IBS) (A) and Bacterial soft rot (B)**.**

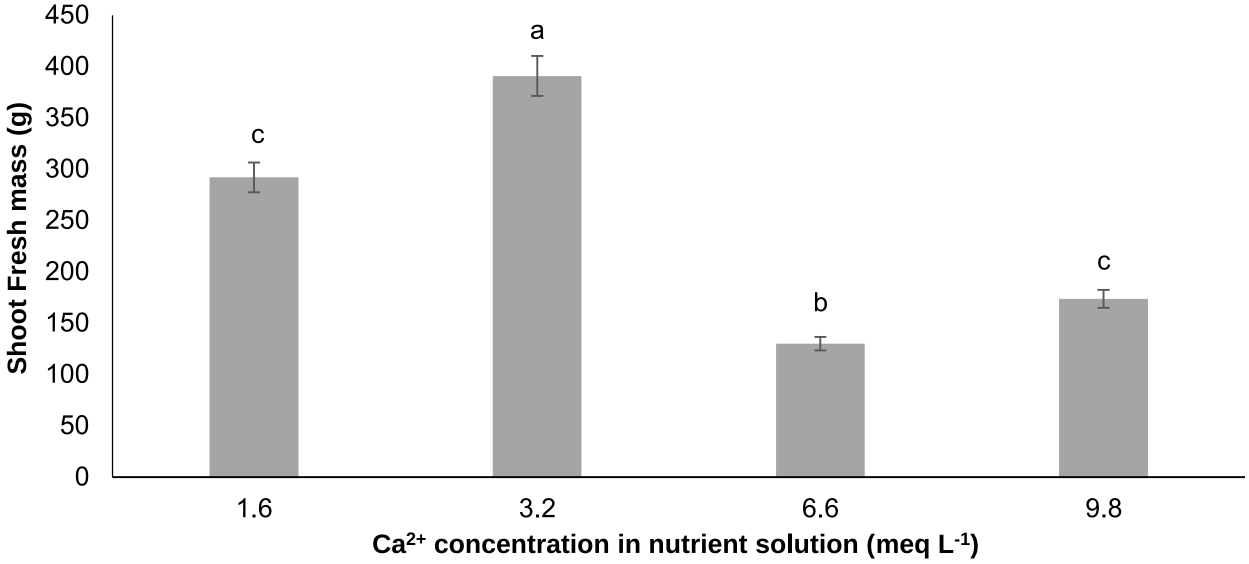
Table 2.1: Nutrient solution composition for the four solutions with different Ca levels applied to the four potato cultivars included in this trial. Concentration (meq L^{-1}) of macro and micro elements all at an EC of 1.5 mS cm^{-1} is indicated

	NH_4^+	K^+	Ca^{++}	Mg^{++}	NO_3^-	$H_2PO_4^-$	$SO^{4=}$	Cu	Mn	Zn	B	Fe	Mo
	meq L^{-1}							mg L^{-1}					
Control	0.66	5.4	**6.6**	3.0	9	0.8	5.2	0.05	0.55	0.25	0.3	1	0.05
Low Ca	0.16	8.5	**1.6**	4.9	9	0.8	5.2	0.05	0.55	0.25	0.3	1	0.05
Medium Ca	0.32	7.6	**3.2**	4.2	9	0.8	5.2	0.05	0.55	0.25	0.3	1	0.05
High Ca	0.90	3.3	**9.8**	1.9	9	0.8	5.2	0.05	0.55	0.25	0.3	1	0.05

Results and Discussion

Shoot fresh and dry mass

Calcium (Ca) application levels influenced the fresh mass of the shoot significantly (Figure 2.1). The highest shoot fresh mass was recorded for plants from the medium Ca application levels (3.2 meq Ca L^{-1}). This was significantly higher than the shoot fresh mass of plants grown at either a high (9.8 meq Ca L^{-1}) or low Ca (1.6 meq Ca L^{-1}) application levels. Plants grown at the standard Ca application level (6.6 meq Ca L^{-1}) showed a significant reduction in vegetative growth, with a shoot fresh mass of 130 g $plant^{-1}$ compared to 174 g $plant^{-1}$, 292 g $plant^{-1}$ and 391 g $plant^{-1}$ at the high, low and medium Ca application treatments respectively. Shoot fresh mass thus increased with the increase in Ca application levels up to the Ca application level of 3.2 meq Ca L^{-1} and then decreased as the Ca application level was further increased to 9.8 meq Ca L^{-1} (Figure 2.1). Kazemi (2013) found that Ca (10 mM) either alone or in combination with humic acid (20 ppm HA^{+} 10 mM Ca) increased the vegetative and reproductive growth, yield and chlorophyll content of tomatoes (*Solanum lycopersicum*). According to Özgen and Palta (2000) Ca does not have an influence on plant development under conducive growing conditions but Ca is likely to have a greater influence on plant parts under heat stress. It is possible that the results observed during this trial was also as a result of heat stress since the average temperatures during this period was 28°C maximum temperature and 14°C for minimum temperature. Shoot fresh mass being higher at 3.2 meq L^{-1} might be due to the imbalances between elements in the nutrient solution. Salim (2002) found that fresh mass of the plant shoot increased with an increase in the amount of K.

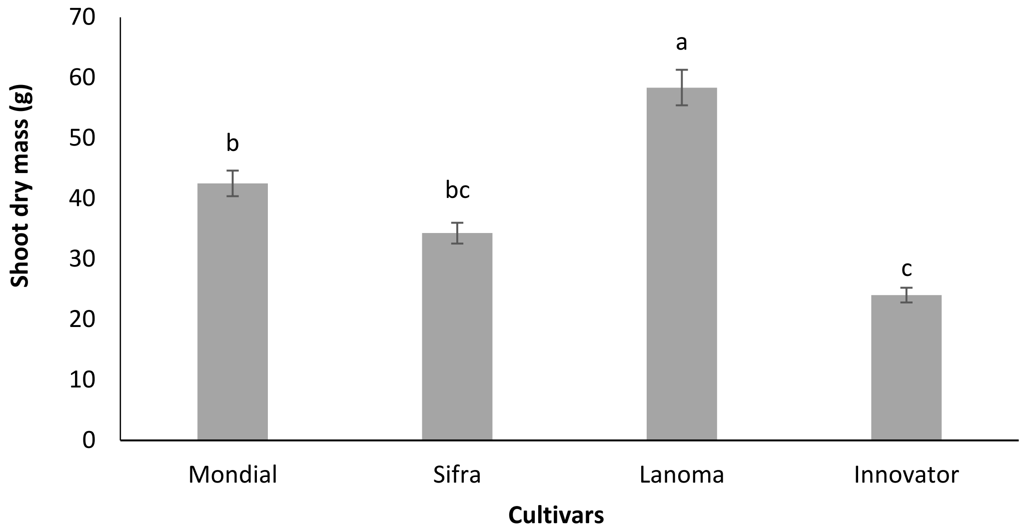


ANOVA	F-value	Pr>F	Significance
Treatment	15.4392	0.0000	**

** P<0.01; ns, not significant at P=0.05

Figure 2.1: The effect of different calcium treatment levels on shoot fresh mass of potato plants. Different letter symbols above bars indicate significant differences at P=0.05.

There were significant differences in shoot dry mass between Innovator and Mondial and also between Innovator and Lanorma (Figure 2.2). Innovator yielded the lowest shoot dry mass (24 g). Shoot dry mass of Lanorma was significantly higher (58 g) than all the varieties that were evaluated. This indicates that Lanorma was not negatively influenced by the high temperatures during the growing season. The data on shoot fresh mass is not shown because it is similar to that of shoot dry mass data.



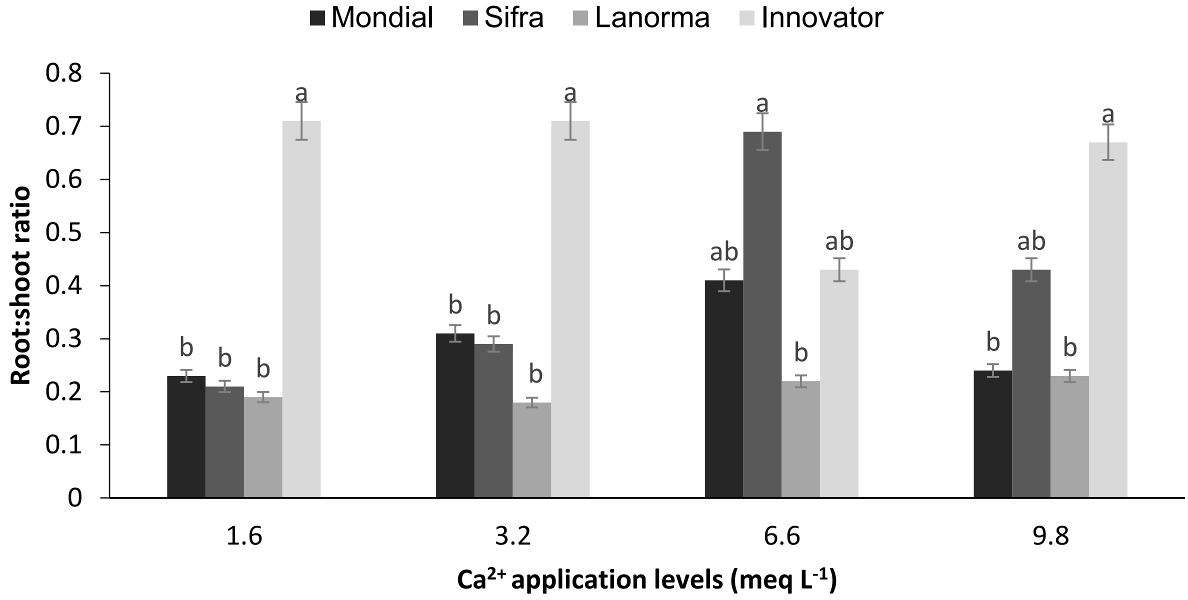
ANOVA	F-value	Pr>F	Significance
Cultivar	7.2029	0.0003	**

** p<0.01

Figure 2.2: Shoot dry mass of plants of four potato cultivars cultivated with different Ca application levels four during the growing season. Different letter symbols above bars indicate significant differences at P=0.05.

Root:Shoot ratio

The root:shoot ratio was affected by both the Ca application level and also differed between the cultivars. The significant interaction between these two main effects is shown in Figure 2.3. Andrews et al. (1999) stated that supplying macronutrients can affect the partitioning of dry matter between shoot and roots. Root of higher plants and that shoot to root ratio decreases when growth is limited by N supply (Andrews 1993). In correlation with the present study, Ca application in this trial positively influenced the partitioning of dry matter between roots and shoots. In the two lower Ca treatments (1.6 and 3.2 meq L^{-1} Ca), the root:shoot ratio of Innovator was significantly higher than that of the other three cultivars. At the two higher Ca treatments (6.6 and 9.8 meq L^{-1} Ca), the root:shoot ratio of Innovator was only significantly higher than that of Lanorma. In the control treatment (6.6 meq L^{-1} Ca), Sifra had a higher root:shoot ratio compared to Lanoma whereas there was no significant difference in root:shoot ratio between these two cultivars at the other Ca application concentrations. The root:shoot ratio of both Lanorma and Mondial was however constant throughout and thus not affected by the Ca application rate. This was due to low shoot production from Innovator (Shown on Fig 2.2), then at higher Ca (9.8 meq L^{-1}), the plants grew better under heat stress resulting in more shoots and thus lower root:shoot ratio.



ANOVA	F-value	Pr>F	Significance
Treatment*Cultivar	2.1472	0.0376	*

*P<0.05

Figure 2.3: Interaction between calcium (Ca) application level and different cultivars on root: shoot ratio. Low Ca was supplied at 1.6, medium Ca at 3.2, control Ca at 6.6 and high Ca at 9.8 meq L^{-1}. Treatments followed by different letters differ significantly at P=0.05.

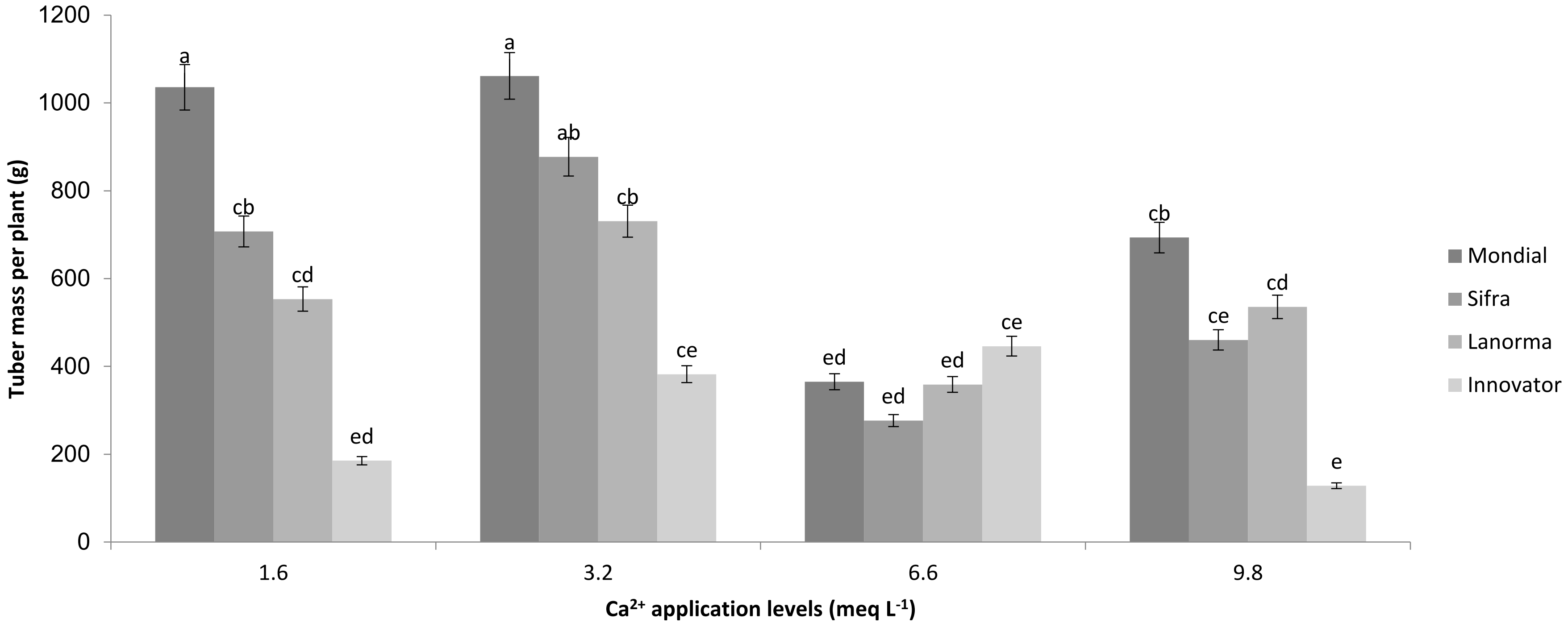
Tuber fresh mass

A significant interaction was observed for the tuber fresh mass with regards to the Ca application level and the cultivar used during this trial (Figure 2.4). For Mondial and Sifra the tuber yield was higher at the two lower Ca application levels (1.6 and 3.2 meq L^{-1}) while for Lanorma and Innovator there was no significant difference in tuber yield between the different Ca application levels. Mondial had a significantly higher yield at the lowest Ca application level (1.6 meq L^{-1} Ca) compared to the other cultivars tested. (Figure 2.5). At the highest Ca application level, the yield obtained from Innovator was significantly lower than that of the other three cultivars. El-Beltagy et al. (2000) also found tuber yield tended to increase with increasing Ca application to medium levels (15 and 21.6 g $plant^{-1}$). Modisane (2007) found that 15 t ha^{-1} of gypsum resulted in higher tuber yields, but the yield decreased when the highest (40 t ha^{-1}) level of gypsum level was applied. This might be due to excessive amounts of Ca in the soil that reduces the uptake of other nutrients such as potassium (K) and iron (Fe) (Malvi 2011), resulting in lower yields. It is however also possible that in this trial the slightly higher application of K that occurred at the lower Ca applications resulted in this increase in yield. Westerman et al. (1994) found that K applications increased potato yields independent of the K-source.

Average tuber mass was not significantly influenced by either different calcium application levels (Table 2.2) or different cultivars (Data not shown). However, Mondial yielded higher yields (112.3 g tuber^{-1}) than Lanorma (66.0 g tuber^{-1}). Higher tuber yields for Mondial could be due to the fact that environmental conditions were conducive for Mondial compared to Lanorma. According to Jasim (2013), potato cultivars differ in growth and yield because of the differences in inheritance and the ecological conditions.

Tuber number

Average number of tubers per plant was significantly influenced by different calcium application levels (Figure 2.6). Plants treated with 3.2 meq L^{-1} yielded higher tuber numbers (9.3) than plants that was treated with 6.6 and 9.8 meq L^{-1} (6.6 and 6.1 respectively). This might be due to the nutrient solution composition that had a higher K^+ composition (7.6 meq L^{-1}) than Ca^{++} (3.2 meq L^{-1}) at medium calcium application level (Table 2.1). This can be supported by Zelelew and Ghebreselassie (2016), where it was revealed that the number of tubers per plant had shown a gradual and significant increase with increasing N levels.



ANOVA	F-value	Pr>F	Significance
Treatment*Cultivar	2.0912	0.0420	*

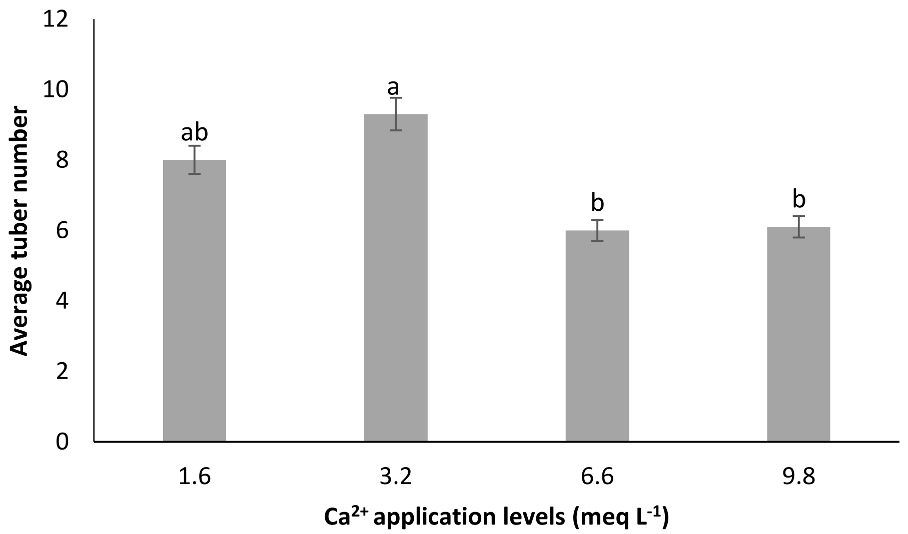
** P<0.05;*

Figure 2.4 Interaction between Ca application level (meq L^{-1}) and different cultivars on tuber fresh mass per plant. Treatments followed by different letters differ significantly at P=0.05).

Table 2.2: Influence of different calcium application levels (low calcium supplied at 1.6, medium calcium supplied at 3.2, control calcium supplied at 6.6 and high calcium supplied at 9.8 meq L^{-1}) on average tuber mass. Treatments followed by different letters differ significantly P=0.05)

Ca concentration (meq L^{-1})	Average tuber mass
1.6	83.0a
3.2	105.0a
6.6	77.0a
9.8	87.5a
Significance	ns

ns, not significant at p=0.05



ANOVA	F-value	Pr>F	Significance
Treatment	4.8825	0.0047	*
Cultivar	2.3835	0.0803	ns
Treatment*Cultivar	1.3626	0.2303	ns

*** p<0.01; ns, not significant at P=0.05, P<0.05*

Figure 2.5: Effect of different calcium application levels (low calcium supplied at 1.6, medium calcium supplied at 3.2, control calcium supplied at and high calcium supplied at 9.8 meq L^{-1}) on average tuber number. Treatments followed by different letters differ significantly at P=0.05).

Harvest index

Harvest Index (HI) was significantly different between cultivars (Table 2.4). Mondial had higher HI than Lanorma and Innovator. However, HI was not significantly influenced by the different

Ca application levels (Table 2.5). The results presented for this trial, show HI values which range from 0.6 - 0.8. Harvest index (HI) is an indication of the sources stored in the tubers taken from the biomass of the plant and how efficient the plant was in allocating resources (assimilates) to the tubers (Foulkes et al. 2007; Gutam 2011; Mazid et al. 2013). Mazurczyk et al. (2009) stated that among cultivated plants, potato is characterised by the highest values of harvest index. The results from this study shows that the potato plants of all cultivars were very efficient in transporting resources from the shoot to the tubers and that resource allocation was not affected by Ca application levels. A similar trend was observed in the study by Mazurczyk et al. (2009), where HI was high for the plants with low above ground mass.

Table 2.4: Harvest Index (HI) of four potato cultivars subjected to different calcium application levels

Cultivars	**Harvest index**
Mondial	0.71a
Sifra	0.71a
Lanorma	0.58b
Innovator	0.56b
Significance	*

** P<0.05;*

Table 2.5: Influence of different calcium application levels (low calcium supplied at 1.6, medium calcium supplied at 3.2, control calcium supplied at 6.68 and high calcium supplied at 9.8 meq L^{-1}) on Harvest Index (HI).

Treatments	**Harvest index**
1.6	0.63a
3.2	0.59a
6.6	0.66a
9.8	0.68a
Significance	ns

ns, not significant at P=0.05

Visual quality of tubers

Visual quality of tubers was significantly influenced by different calcium application levels (Fig 2.6). The data is descriptive qualitative. A high percentage (95%) of tubers without defects was obtained on plants that only received a standard nutrient solution (control). Plants that were treated with 3.2 meq L^{-1} Ca yielded 69% of tubers which was not defected. A high percentage (56%) of defected tubers were observed on tubers that was treated with 1.6 meq L^{-1} Ca. Potato Network South Africa (2008) reported that both internal browning and hollow heart occur if periods of heat and water strain are experienced during the growth season. Under these conditions cell expansion will be accelerated but Ca uptake will be limited. The high heat during the growth season of this trial could therefore have resulted in localised Ca deficiencies, increasing the incidence of defected tubers. Visual quality of tubers was significantly different between cultivars (Fig 2.7). Tubers from the cultivar Lanorma yielded tubers with a high visual quality. A high percentage (89%) of the Lanorma tubers was classified as having a good visual quality with few observations of tubers which did not have good visual quality (11%). According to the United Kingdom Agriculture and Horticulture Development Board (2011), Lanorma has resistance to splitting and also good resistance to bruising. Tubers from Mondial and Sifra had a good visual quality with 65% and 66% of the tubers rated good.

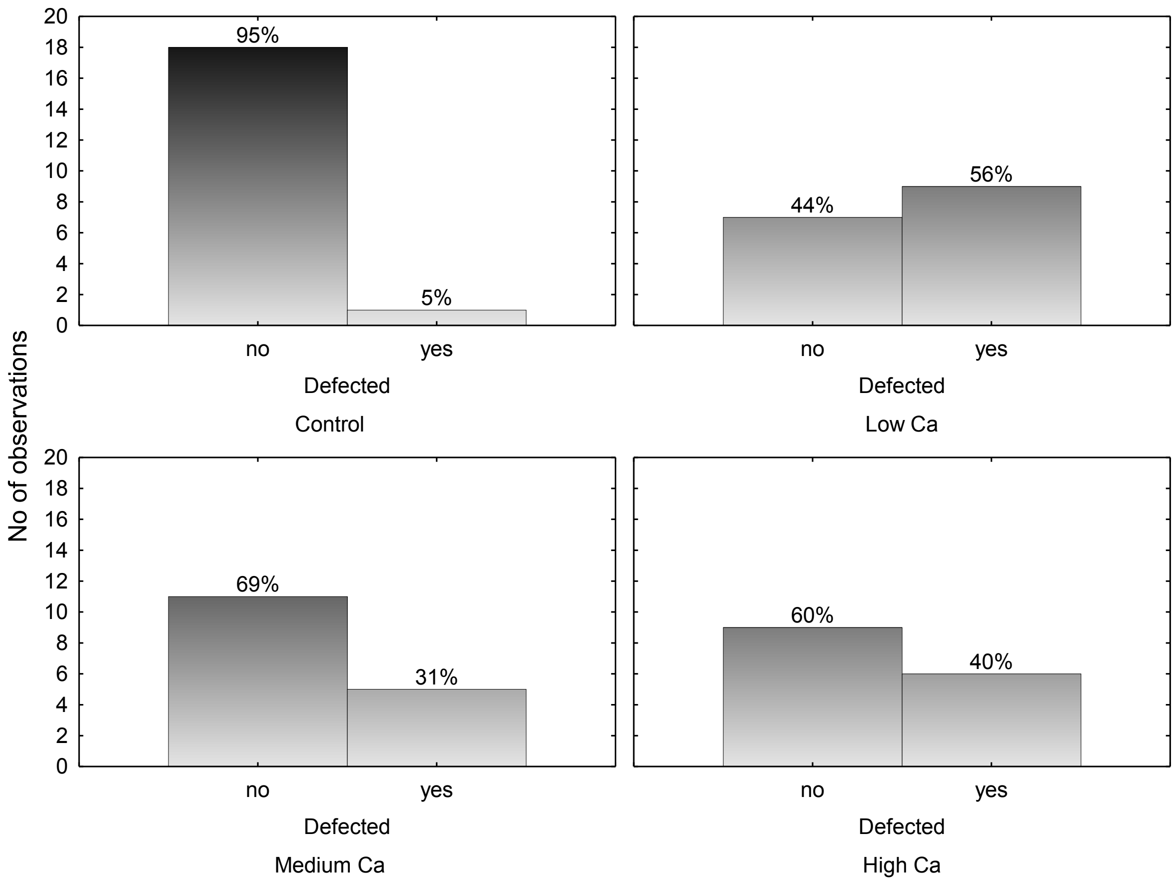


Figure 2.6 Influence of different calcium application levels (low calcium supplied at 1.6, medium calcium supplied at 3.2, control calcium supplied at and high calcium supplied at 9.8 meq L^{-1}) on different potato cultivars and the number of observations.

Mondial and Sifra cultivars yielded tubers which had the highest number of tubers which did not have good visual quality (35%). The reason for poor visual quality in Mondial might be the result of heat stress, since this trial was planted in September when temperatures were not conducive for Mondial. According to the FAO (2008), optimum yields are obtained where average temperatures are in a range of 18 to 20°C. The maximum average temperature from September to December in Stellenbosch is 25 °C. Some of the tubers from Sifra were classified as having a poor visual quality because they were bruised after harvesting. The reason for bruising in potatoes are poor skin set that might be a result of deficiencies of potassium (K) or might be due to tubers were harvested before skin setting was completed. It has been reported that tuber physical maturity is characterised by the death of the shoot, and is accompanied by skin setting (Kumar et al. 2005).

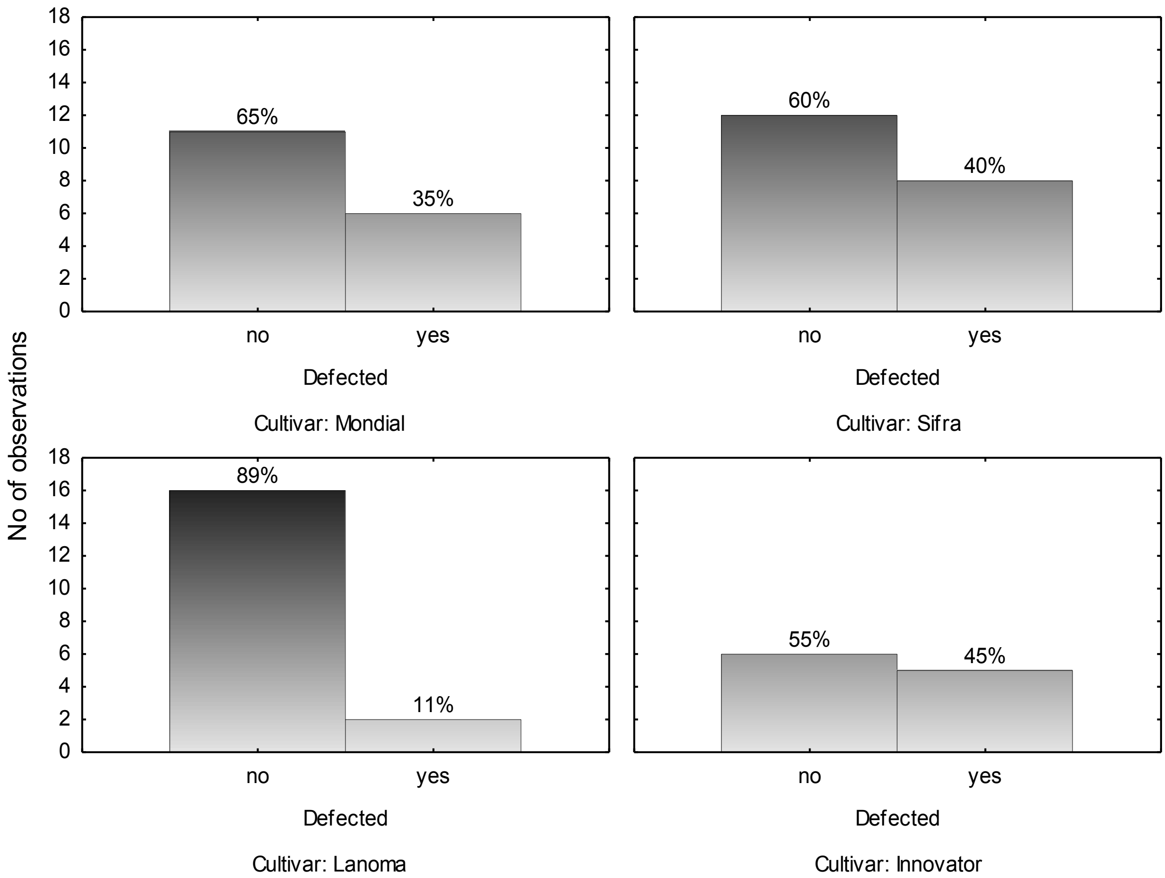


Figure 2.7 Different potato cultivars categorized according to the tuber visual quality (Good, Not good and Bad) and the number of observations.

Conclusions

Potato vegetative growth as well as tuber yield was significantly influenced by Ca application levels (1.6, 3.2, 6.6 and 9.8 meq L^{-1}) and also differed between the cultivars (Mondial, Sifra, Lanorma and Innovator). Mondial performed better in terms of tuber yield, harvest index and shoot dry mass while Lanorma performed better in terms of tuber quality. The root:shoot ratio of Innovator was significantly higher than that of the other three cultivars. For Mondial and Sifra the tuber yield was higher at the two lower Ca application levels (1.6 and 3.2 meq L^{-1}) while for Lanorma and Innovator there was no significant difference in tuber yield between the different Ca application levels. Average tuber mass was not significantly influenced by either different Ca application levels or different cultivars. Plants treated with 3.2 meq L^{-1} yielded more tubers than plants that was treated with higher Ca levels (6.6 and 9.8 meq L^{-1}). A high percentage (95%) of tubers without defects was obtained on plants that only received a standard nutrient solution (control). Plants that were treated with 3.2 meq L^{-1} yielded 69% of tubers which was not defected. A high percentage (56%) of defected tubers were observed on tubers that was treated with 1.6 meq L^{-1}. The conclusion that can be drawn from this trial is that increasing Ca application above 1.6 results in higher quality tubers as well as higher yields. It is possible that increasing the Ca application rate above this level negatively affects the uptake of other cations, resulting in a negative effect on growth and tuber quality. It was also observed that although not directly measured, high temperatures during crop growth can be detrimental to potato production, however, according to this study, for high yield purposes, 3.2 meq L^{-1} level is recommended, while 6.6 meq L^{-1} is recommended for quality, especial for food processing companies.

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CHAPTER 3

Influence of different calcium application levels on potato plants under low temperature growing conditions.

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Abstract

The potato (*Solanum tuberosum L*.) is an adaptable crop, and modern varieties make its cultivation practicable in numerous parts of the world. Calcium transport being limited in the phloem results in low tuber calcium content, which cause physiological disorders. Environmental as well as root-zone conditions also affect the uptake and translocation of calcium. Therefore the present study aims to investigate the influence of different calcium application rates in 3 different soil types (sandy, sandy loam and loam soil) during a winter growing season on potato tuber yield and quality aspects. Potato seedlings, prepared from cultivars Destiny and Lanorma, were transplanted to 3 m^3 bins containing the different soils. Three fertiliser application rates (1.6, 3.2 and 6.6 meq Ca L^{-1}) were applied through drip irrigation. The interaction between Ca application levels and cultivars significantly influenced tuber mass, shoot fresh and dry mass. Plants fertigated with 1.1 meq L^{-1} Ca in sandy loam yielded tubers which had higher tuber fresh mass than plants that were fertigated with 6.6 meq L^{-1} in sandy loam. Different calcium levels did not influence the concentration of macro and micro elements in potato tubers. Low yields obtained in this trial were due to low temperatures during the growing season, as the trial was planted in winter.

Key words: Calcium, low temperature, potato, soil type, tubers

INTRODUCTION

The potato (*Solanum tuberosum L*.) is an adaptable crop, and modern varieties make its cultivation practicable in numerous parts of the world (Okazawa 1967). Potato production can be restricted by long photoperiods or suboptimal temperatures since tuber formation is completely prevented under these conditions (Lezica 1970). Van Loon (1981) reported that water stress and high temperatures were the most important factors that negatively affect the yield and quality of potato tubers. According to Drost (2010), potatoes prefer a sunny location, a long growing season, and fertile, well-drained soil for optimum yields. Potatoes grow well on a wide variety of soil types, in both slightly acidic soils, and in alkaline soils (Department of Agriculture and Food 2013).

South Africa has a wide variety of different climates, which range from a continental climate with dry winters and rainy summers, to a Mediterranean climate with dry warm summers and rainy winters in the south western coastal areas (Taljaard 1986). Haverkort et al. (2013) reported that potatoes are grown in most of these climatic regions with dry or rainy winters and summers. The potato plant is shallow-rooted and sensitive to water and nutrient deficits (Prunty and Greenland 1997). Drost (2010) emphasised that potatoes require good soil moisture levels throughout the growing season. The use of drip irrigation has been increased in most crop commodities, mainly for vegetables and fruits, to improve water use efficiency and nutrition supply in Mediterranean cropping system (Onder et al. 2005). Miller and Martin (1987) found that tuber yield is reduced by water stress, especially during the tuber bulking stage.

Potato sprout growth is initiated following a period of endo-dormancy (Sonnewald 2001). Cold temperatures (3°C) can be stressful to the tubers and can hasten sprouting (Burton et al. 1992). Patsalos (2005) found that low temperatures (3˚C) drastically affect the potato crop by damaging the foliage. Under low input conditions, sprouting can be promoted by placing tubers in pits lined with dry leaves and covered with straw (MoA and GTZ 1998). However, Crissman et al. (1993) reported that tubers sprouted in pits are of poor quality due to apical dominance and shoot etiolation caused by the dark conditions. Storing tubers in dark conditions results in production of extensively long etiolated sprouts as opposed to dark green leaves and expansive plant from tubers exposed to light (Crissman et al. 1993). Frazier et al. (2004) reported that poor maintenance of sprout control may result in a drastic reduction of tuber quality. There is often little time between the growing periods to permit adequate sprouting of the tubers (Crissman et al. 1993; Maingi et al. 1992). Sprouting during storage results in mass loss and may impede airflow through the potato pile (Frazier et al. 2004).

Calcium (Ca) is usually relatively adequate in soils and this nutrient rarely limits crop production (Kirkby and Pilbeam 1984; Kelling and Schutte 2004). On arable soils, plants rarely show signs of Ca deficiency, as Ca is one of the more abundant cations in soil solutions. Calcium deficiency may however be a problem on acid soils. Calcium is a positively charged cation (Ca^{2+}) held on soil clay and organic matter particles. Soils low in Ca often have a low pH and require lime (Kelling and Schutte 2004). The study conducted by Wallace & Hewitt (1948) showed that tubers planted in soil with pH values in the order of 4.0 failed to emerge because of death of the sprout apex caused by Ca deficiency. Simmons and Kelling (1987) stated that on sandy soils where there’s low cation exchange capacity and where the soil Ca is low, potato tuber Ca levels may not be optimal for maximum yield or quality.

In potatoes as well as many other economically important vegetables and fruits, physiological Ca disorders may seriously reduce product quality (Bangerth 1979). Tuber Ca content range from 0.009 to 0.06 g Ca $100g^{-1}$, while shoots contain 1.5 % per dry mass (Collier et al. 1978; 1985; Kempen 2012). Calcium plays a significant role in cell walls and is also important for cell division and elongation, permeability of cell membranes and nitrogen metabolism (Kelling and Schutte 2004). Kirkby and Pilbeam (1984) reported that Ca occurs in minute concentrations in the cytoplasm and chloroplasts and appears to have a limited function as an enzymatic cofactor. Kelling and Schutte (2004) reported that Ca is different from numerous plant nutrients, in a way that it is only moved within the plant with water from the roots through the leaves. Calcium thus moves in the xylem through transpirational mass flow (Bell and Biddulph 1963; Clarkson 1984), and only to a very limited extent in the phloem (Kirkby and Pilbeam 1984). Calcium is actually relatively immobile and it cannot be translocated from the leaves to the tubers (Kempen 2012). Calcium being limited in the phloem results in low tuber Ca contents, which causes physiological disorders (Kratze and Palta 1985). The present study aims to investigate the influence of Ca application under low temperature conditions on potato tuber yield and quality aspects of potatoes in 3 different soil types.

MATERIALS AND METHODS

Experimental site and crop details.

The experiment was carried out in large (3 m^3) containers, simulating field conditions, at Welgevallen experimental farm, University of Stellenbosch, with GPS coordinates: 33°56'33.9"S 18°51'59.0"E. The experiment was laid out as a randomised complete block design arranged as a 2x3x3 factorial. Potato (*Solanum tuberosum L*.) seedlings were prepared from two cultivars (Destiny and Lanorma) on the 4th of April, by removing the eye and 2 cm tuber tissue and placing these in trays with Hygromix® as a medium in a glasshouse.

Hygromix® is high quality Canadian peat based growing medium for seedlings, it consists of vermiculite and macro- and micro-nutrients. The growing period of Destiny is medium, 110 days (Du Raan and van den Berg 2016). Destiny has a moderate dormancy and requires short term storage periods at a temperature of 7°C. Destiny tubers are round to oval with little red shallow eyes and grow in most soil types (Agrico UK 2013). Lanorma has large tubers with oval shape and tolerant to high environmental extremes. Lanorma has an ability to produce a high number of tubers and yields (Real Potatoes 2016). On the 27th of April, seedlings were transplanted to 18 bins filled with 3 m^3 soil, 2 rows (one row per cultivar) with 4 plants in a row, 8 plants per bin, with a total of 144 plants per cultivar. Each bin had one of nine treatment combinations (3 Ca levels x 3 soil types) with the two cultivars planted in every bin as a split plot. The treatments were replicated twice. Three fertiliser levels Ca1, Ca2 and Ca2 (1.6, 3.2 and 6.6 meq Ca L^{-1} respectively) were applied via drip irrigation to limit crossover between treatment bins during the crop growth after transplanting.

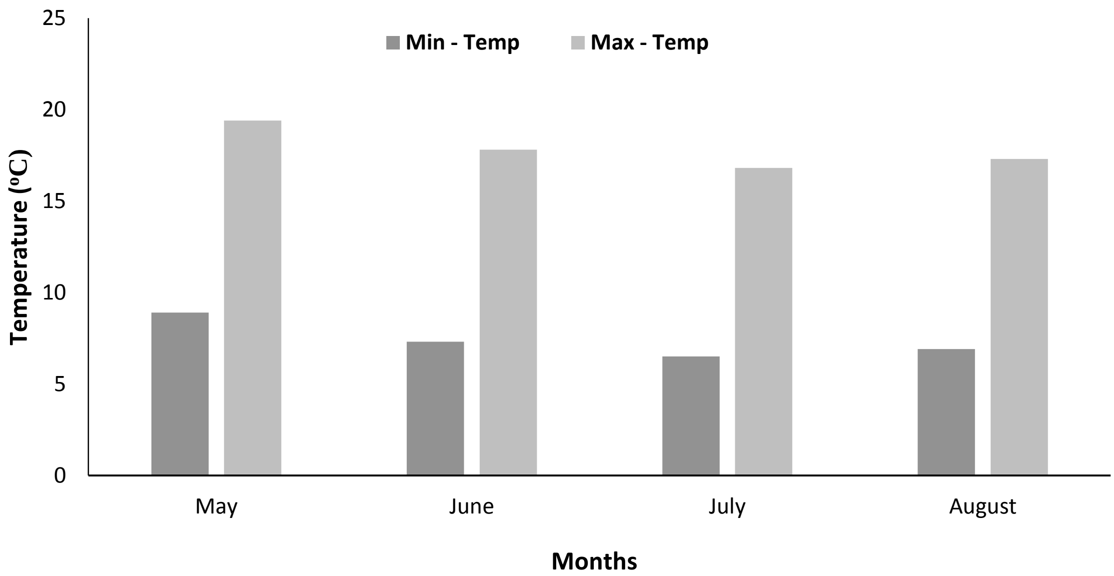


Figure 3.1: Minimum and maximum temperatures in Stellenbosch during May to August 2016. Data by Stellenbosch Weather service.

Three different soil types were used, sandy, sandy loam and a loamy soil. The soil pH and EC were also determined; analysis was done at University of Stellenbosch, Agronomy laboratory. A full soil analysis was done before the start of the trial and at the end of the trial for chemical analysis in the laboratory in order to determine changes in the chemical composition of the soils (Table 2.1). Fertiliser applications were done according to the soil analysis for each soil as shown in Table 2.2. Plantlets were fertigated twice daily with a nutrient solution ($Ca(NO_3)_2$) at an electrical conductivity (EC) of 1.5 mS cm^{-1}, at 8:00 and 16:00.

Table 3.1. The macro- and micro nutrient concentrations (% and mg kg^{-1}) of the three different soil types used for cultivating the potatoes.

Soil types	Na	K	Ca	Cu	C	Mn	B	S	Zn	Mg
	mg kg^{-1}	%	%	mg kg^{-1}	%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	%
Sandy soil	18	17	0.96	0.16	0.08	4.48	0.03	3.30	1.26	0.31
Sandy Loam	33	91	4.89	0.44	0.73	10.38	0.19	9.70	7.03	0.82
Loam	41	253	3.36	2.25	0.74	61.83	0.33	6.60	8.11	0.66

Table 3.2. Nutrient solution composition of the three Ca application levels (1.1, 3.2 and 6.6 meq L^{-1}) applied via drip irrigation to the potato plants. Each solution had an electrical conductivity (EC) of 1.5 mS cm^{-1}.

	Application (g 1000L^{-1})		
Macro-nutrients	**Ca1**	**Ca2**	**Ca3**
KNO_3	242.4	141.4	585.8
K_2SO_4	191.4	26.1	87.0
KH_2PO_4	108.8	108.8	108.8
$Ca(NO_3)_2.2H_2O$	660.0	160.0	320.0
$MgSO_4.7H_2O$	369.0	602.7	516.6

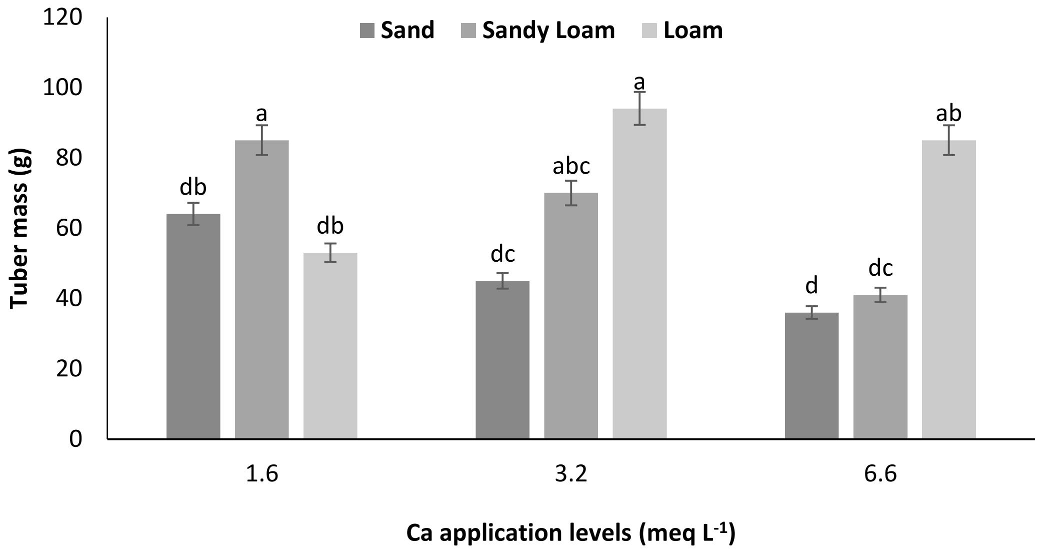
Data collected

The influence of Ca fertilisation on potato tuber yield and on the quality aspects of potatoes was identified 61 days after planting (DAP). The yield was determined through measuring the tuber and shoot fresh mass per plant. After determining the fresh mass, shoot and tuber samples were oven-dried at 82°C for 3 days then weighed to determine the dry mass. Tuber chemical analysis as a parameter for tuber quality was determined through macro- and trace elements analyses (method 6.1.1 for feeds and plants, Alasa handbook of feeds and plant analysis). Ash samples were dried overnight and made up in a 1:1 HCl solution, filtrate and read on Inductively Coupled Plasma (ICP). Chemical analysis was done to determine the effect of Ca application levels on other nutrient levels. These quality tests were done at Stellenbosch Agronomy lab and at the labs of the Western Cape Department of Agriculture, Elsenburg. Tubers were graded according to size: Small (<20g), Medium (>20 - 80 g) and Large (>80g). Three tubers per sample were randomly selected, peeled and sliced for the determination of chemical analyses. The statistical analysis was done using ANOVA, and means comparison ($P<0.05$) using a linear model (Fisher LSD method) (Statistica 2012).

Results and discussion

Tuber fresh mass

An interaction was observed for the tuber fresh mass with regards to different soil types and Ca application levels used during this trial (Figure 3.1). Fresh mass is the sum of plant water content and dry matter production (photosynthesis), thus any environmental factor affecting any of these parameters reflects on the tuber fresh mass (El-Beltagy et al. 2000). There were no differences in yield for plants grown in sandy soil at the different Ca concentrations (Figure 3.1). Plants in the sandy loam soil had higher yields at the low Ca application level (1.1 meq Ca L^{-1}) compared to the high Ca application level (6.6 meq Ca L^{-1}). In contrast in the loam soil the tuber yield was higher at a Ca application level of 3.2 meq Ca L^{-1} compared to the low Ca application level of 1.1 meq Ca L^{-1}. From the observation, conclusion that can be drawn is that there was an inverse relationship, in a way that as the Ca concentration increased in sandy loam, tuber fresh mass decreased while in the loam soil it tended to increase with an increase in Ca application rate. In contrast, Simmons and Kelling (1987) noted consistent improvement in tuber yield and grade with Ca application to soils with Ca levels between 250 and 350 mg kg^{-1}, while less consistent results occurred at higher soil Ca levels. The study by El-Beltagy et al. (2000) showed a similar trend, where there was a decrease in tuber yield with an increase in Ca concentration. This might be due to the abundant amounts of Ca in the root-sphere that hinders the uptake of other nutrients by the roots (Malvi 2011), which might also result in yield loss.



ANOVA	F-value	Pr>F	Significance
Soils	4.9535	0.0093	**
Ca Application	0.5215	0.5955	ns
Soils*Ca Application	4.8774	0.0014	**

** P<0.01; ns, not significant at P=0.05

Figure 3.2: The effect of different calcium treatment levels on potato tuber mass. Plants were grown in different soil types; sand, sandy loam and loam, Different letter symbols above bars indicate significant differences at P = 0.05.

Chapman (1965) stated that cation exchange capacity is the total exchangeable cations in the soil solution. Mengel (2011) reported that dark and light colored loamy soils have higher cation exchange capacity (10-20 meq $100g^{-1}$) than light coloured sandy soils (3-5 meq g^{-1}). Astera (2014) found that the base saturation for Ca, Mg and K in the soil was 15, 4 and 1 % respectively and the ratio provided sufficient levels of nutrients to the crop. According to the present study, it can be concluded that loamy soil had a higher cation exchange capacity than sand and a high base saturation. Sandy loam had higher Ca content than loam soil because according to the soil analysis, loam soil had lower pH than sandy loam. According to Northeast Region Certified Crop Adviser (NRCCA) (2010), low pH reduces the availability of macro- and secondary nutrients. This implies that Ca^{2+} was highly exchanged in cation binding sites in loamy soil particles, which increased it availability to the roots for absorption.

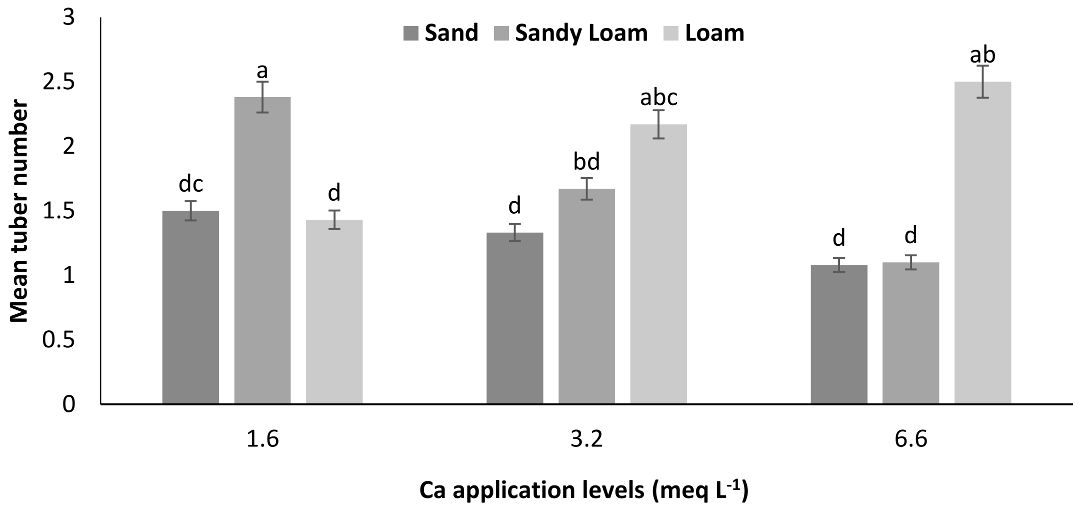
The cultivars also differed with regards to the tuber mass yielded. According to the results of this trial, tuber mass of Destiny was significantly higher than Lanorma (Figure 3.3). This might indicate that the cooler temperatures favoured Destiny more than Lanorma.

ANOVA	F-value	Pr>F	Significance
Cultivar	7.8064	0.0065	**

** P<0.01

Figure 3.3: Tuber mass of two potato cultivars. Different letter above bars indicate significant differences at $p < 0.05$.

An interaction was also observed for the mean number of tubers with regards to the Ca application level and the different soil types used during this trial (Figure 3.4). Plants grown in sandy soil yielded the same number of tubers regardless of the Ca application level while plants in the sandy loam had more tubers per plant when the Ca application level was only 1.6 meq Ca L^{-1}. In contrast plants in the loam soil yielded fewer tubers when a low Ca concentration was applied (Figure 3.4). This trend in the loam soil correlates with the study of Modisane (2007) where the Ca application level (2.2, 8.95, 17.6 and 35.2 meq Ca L^{-1}) influenced tuber number positively, but high Ca application rates resulted in a reduction of tuber number (16, 16, 18, and 13) per plant, respectively. The study by Ozgen and Palta (2005) also showed that the overall tuber number per plant was significantly influenced positively by Ca application. Overall the number of tubers per plant was very low which could be attributed to the low temperatures during the growing season, as the trial was planted in winter (May to July 2016). The average minimum and maximum winter temperatures in Stellenbosch were 7.4 and 18 ˚C (Stellenbosch Weather 2016). A similar study by Patsalos (2005) reported that low temperatures (3°C) are detrimental to potato growth.



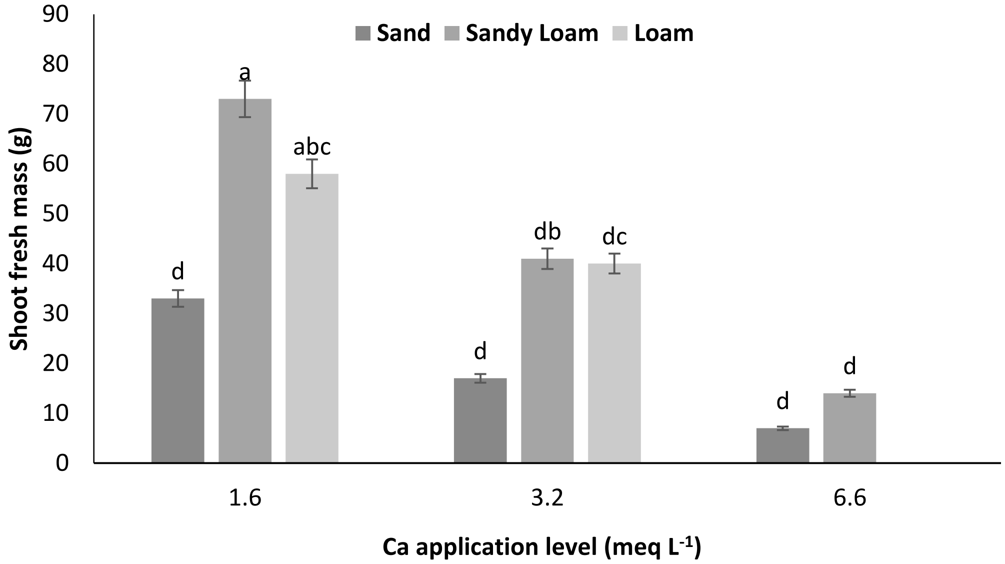
ANOVA	F-value	Pr>F	Significance
Treatment*soil	17.1130	0.0000	**

** P<0.01

Figure 3.4: The influence of different calcium levels on mean tuber number for potato plants grown in different soil types. Different letters above bars indicate significant differences at P = 0.05.

Vegetative growth

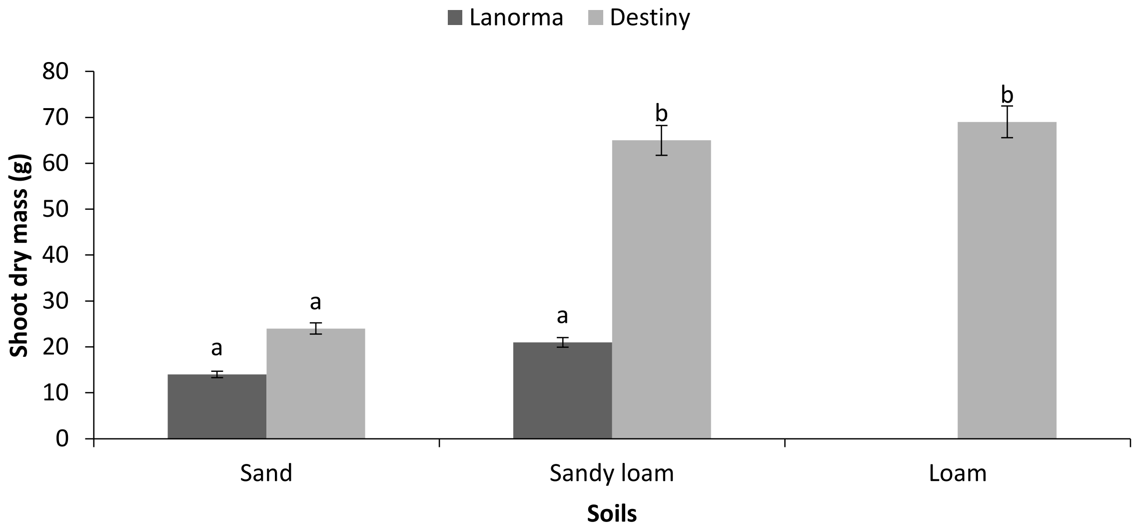
An interaction was observed for the fresh shoot mass with regards to the Ca application level and the different soil types used during this trial (Figure 3.5). With regards to the missing values on the graphs, some of the plants in this trial were severely affected by the leaf blight which occurred after rainfalls, thus this phenomenon might have contributed to the low yields obtained in this trial. Potato plants grown in the sandy soil did not differ with regards to their shoot fresh mass regardless of the Ca application level. In the sandy loam soil plants had a higher shoot fresh mass at the lowest Ca application level (1.6 meq Ca L^{-1}). Simmons and Kelling (1987) reported that Ca transport in the xylem to the shoot produced Ca concentrations sufficient for normal vegetative growth and development. In contrast, Drost (2010) found that heavy fertilisation of potatoes encouraged excessive foliage growth and delays tuber growth. The influence of different soil types on the shoot dry mass of different potato cultivars was significantly different (Figure 3.6). In the sandy soil no difference between the cultivars was observed but in the sandy loam soil the shoot fresh mass of Destiny was significantly higher than that of Lanorma and also higher than either cultivars in the sandy soil. Low shoot fresh mass might be due to low temperatures which severely affected the foliage of the plants during the winter growing season. According to Patsalos (2005), potato plants are very sensitive to low temperatures (3°C), and can cause serious damage in the foliage.



ANOVA	F-value	Pr>F	Significance
Soils	6.0153	0.0034	**
Ca Application	11.7939	0.0000	**
Soils*Ca Application	2.5967	0.0409	*

** P<0.01; *P<0.05

Figure 3.5: The effect of different calcium treatment levels (1.6, 3.2 and 6.6 meq Ca L^{-1}) on shoot fresh mass for potato plants grown in different soil types. Different letter above bars indicate significant differences at P = 0.05



ANOVA	F-value	Pr>F	Significance
Soils*Cultivar	5.7184	0.0046	**

** P<0.01

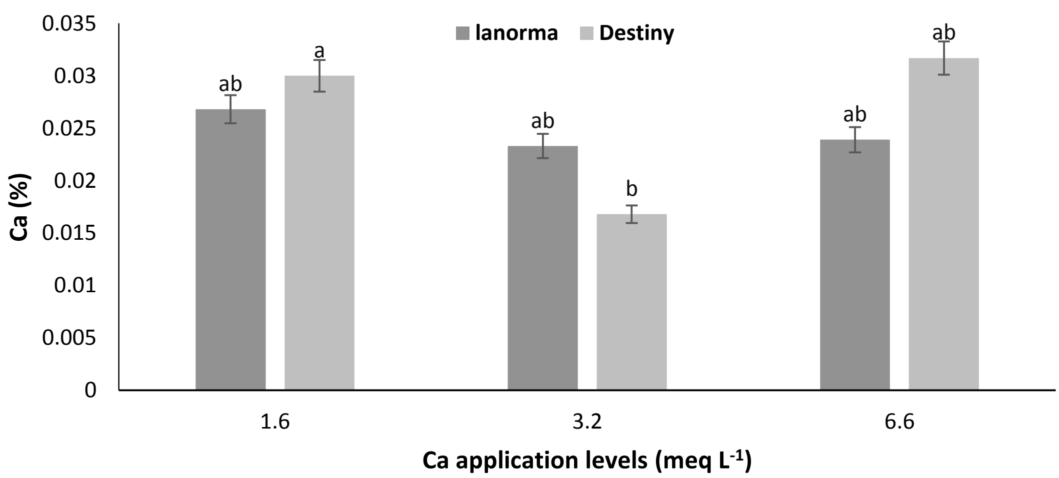
Figure 3.6: Shoot dry mass of different potato cultivars grown on different soil types. Different letter above bars indicate significant differences at P = 0.05.

Chemical composition of tubers

Tuber Ca content was not significantly influenced by application of different calcium levels grown in different soil types (Figure 3.8). The data recorded showed no consistent relations between Ca nutrient content of different cultivars and treatments and no differences between the Ca nutrient content of tubers and treatments were observed, however Destiny plants fertigated with 1.6 meq L^{-1} was significantly higher (0.03%) than the Destiny plants fertigated with 3.2 meq L^{-1} (0.02%). According to Kempen (2012), potato tubers have very low calcium composition, with an average calcium concentration of 0.05 – 0.15 % per dry mass. Simmons and Kelling (1987) found that potato tubers had low levels of calcium due to the limited calcium transport in the xylem and the immobility of calcium in the phloem. The low levels of calcium in tubers might be due to the unavailability of Ca in the root sphere or near stolons during the growing season.

Magnesium (Mg) tuber nutrient showed no significant interaction between Ca levels and soil types. However, Destiny plants fertigated with 6.6 meq L^{-1} yielded tubers which had significantly higher Mg content (0.18%) than the Destiny plants treated with 1.6 meq L^{-1} and 3.2 meq L^{-1} (0.13 and 0.14 % respectively) (Figure 3.9). Clough (1994) reported that Ca fertilisation did not affect concentrations of Mg, B and Zn. Tuber boron (B) results were similar to the Mg results in terms of no sifnificant Ca application level and soil interactions. Lanorma cultivar plants fertigated with 1.6 meq L^{-1} yielded tubers which had significantly higher B content (7 mg kg^{-1}) than Destiny plants fertigated with 1.6 meq L^{-1} Ca (5.7 mg kg^{-1}) (Figure 3.10).

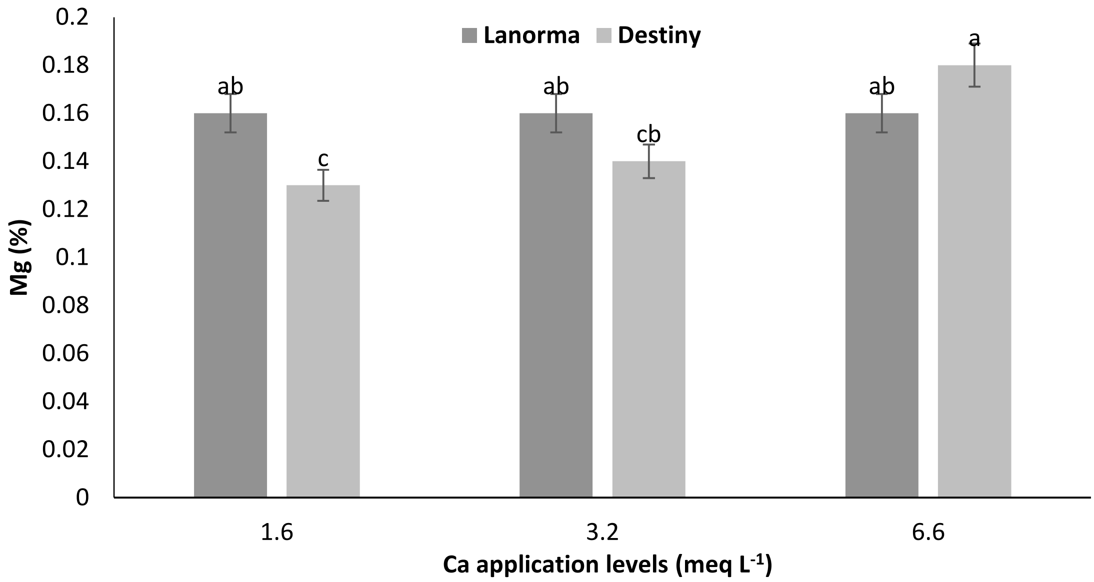
Similar observations was noted in the study by MacVicar et al. (1941), where the B content of tubers ranged from 5.5 to 13.9 µg g^{-1}. This might be because the level of B in the soil was already high before the trial was started (Table 3.1). MacVicar et al. (1941) found that there was no consistent difference between varieties regarding the B content at the different locations. Application of different Ca levels did not influence the concentration of macro and micro elements in potato tubers planted in different soil types (Table 4.3). This was in accordance with what Clough (1994) reported where Ca fertilisation did not affect tuber P, K, Mn, Fe, or Cu concentrations.



ANOVA	F-value	Pr>F	Significance
Ca Application*Cultivar	0.97433	0.3851	ns

ns, not significant at P=0.05

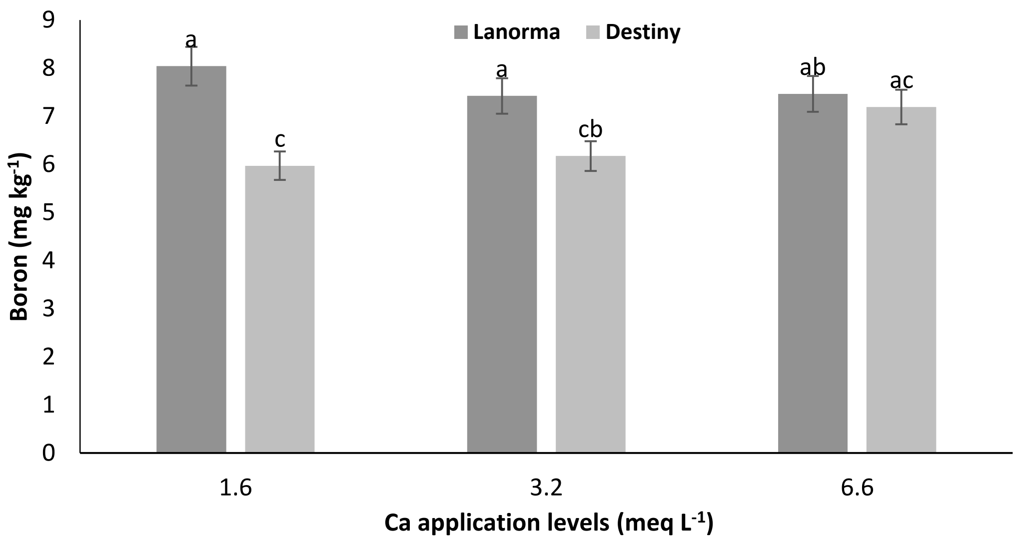
Figure 3.8: Calcium concentration of different potato cultivars fertigated with different calcium application levels. Different letter symbols above bars indicate significant differences at P = 0.05.



ANOVA	F-value	Pr>F	Significance
Ca Application*Cultivar	3.5349	0.0373	*

ns, not significant at P=0.05

Figure 3.9: Magnesium concentration of different potato cultivars fertigated with different calcium application levels. Different letter symbols above bars indicate significant differences at P = 0.05.



ANOVA	F-value	Pr>F	Significance
Ca Application*Cultivar	1.7111	0.119	ns

ns, not significant at P=0.05

Figure 3.10: Boron concentration of different potato cultivars fertigated with different calcium application levels. Different letter symbols above bars indicate significant differences at P = 0.05.

Table 3.3 Different calcium application levels on the concentration of macro and micro elements in potato tubers planted in different soil types

Soils	Treatments	N	P	K	Ca	Mg	Zn	B
	%	%	%	%	Mg kg^{-1}	Mg kg^{-1}	Mg kg^{-1}	Mg kg^{-1}
Sand	Ca1	2.7a	0.4a	2.2a	0.04a	0.1a	1.8a	7.4a
Sand	Ca2	2.4a	0.3a	2.2a	0.01a	0.2a	1.8a	7.0a
Sand	Ca3	2.2a	0.4a	2.6a	0.02a	0.2a	3.1a	7.4a
Sandy Loam	Ca1	2.4a	0.4a	2a	0.03a	0.1a	1.9a	6.8a
Sandy Loam	Ca2	2.8a	0.4a	2.1a	0.02a	0.1a	1.9	6.8a
Sandy Loam	Ca3	2.5a	0.4a	2.2a	0.03a	0.2a	2.3a	6.9a
Loam	Ca1	2.4a	0.4a	2.2a	0.02a	0.1a	1.9a	6.8a
Loam	Ca2	2.3a	0.4a	2.4a	0.02a	0.1a	2a	6.6a
Loam	Ca3	2.9a	0.4a	2.4a	0.04a	0.2a	2.7a	7.6a
ns, not significant at P=0.05		ns	ns	ns	ns	ns	ns	ns

Conclusions

Regardless of the rate of Ca application, tuber yields and vegetative growth for the cultivars evaluated were consistently higher in the heavier soils, sandy loam and loam. This can be expected due to the overall increased availability of nutrients in these soils. Increasing Ca application levels had a definitive positive effect on tuber yield but negative effect on vegetative production in the loam soil. This increase in yield was mainly as a result of an increase in tuber number and not necessarily larger tubers. Tuber initiation and/or tuber retention was therefore positively affected. The two cultivars also differed with regards to yield, with Destiny having larger shoots and yielding more tubers under these growing conditions. Application of different Ca levels did not influence the concentration of macro and micro elements in potato tubers planted in different soil types and the differences in yield can therefore not directly be linked to nutrient uptake. The overall low yields obtained in this trial might be due to low temperatures during the growing season, as the trial was planted in winter (May to July 2016) and the minimum and maximum winter average temperatures in Stellenbosch is 7.4 and 18 ^{O}C.

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CHAPTER 4

Influence of calcium as a foliar application and a soil drench on the growth, yield and quality aspects of potatoes.

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Abstract

The high production potential of the potato (*Solanum tuberosum L.*) ensures that it can contribute significantly to the world's food requirement. Potatoes have a high carbohydrate content and contains high amounts of vitamin C, proteins and nutrients such as phosphorus and calcium. Calcium is an essential macro-nutrient often linked to post-harvest quality of many horticultural crops. In potatoes it has been linked to the incidence of physiological disorders such as internal brown spot and hollow heart. This study investigated the influence of calcium as a foliar application and a soil drench on the growth, yield and quality aspects of potatoes. The experiment was conducted in a greenhouse at Stellenbosch University. Potato seedlings of two cultivars (Lady Rosetta and Mondial), transplanted to sand filled bags were fertigated with a standard nutrient solution. The experiment comprised of 7 treatments where calcium was applied in addition as either a foliar or soil drench from week 6 to week 10 at a rate of 9 meq L^{-1} and 4 meq L^{-1}. Tuber fresh mass and tuber number was not statistically influenced by either foliar or soil drench calcium application, however, specific gravity, percentage shoot dry mass and shoot dry mass and chemical composition of tubers was significantly influenced by either foliar or soil drench calcium application. From these results it appears that Calcium applied at these rates and time of plant development had no benefit on yield or quality aspects of potato tubers.

Keys: Calcium, foliar, potato, soil drench, tubers

INTRODUCTION

The high production potential of the potato (*Solanum tuberosum L.*) ensures that it has the potential to contribute significantly to the world's food requirement. It has a high carbohydrate content and contains high amounts of vitamin C, proteins and nutrients such as phosphorus (P) and calcium (Ca) (Hussein and Hamideldin 2014). Fertilisation is an important factor in potato production, required to obtain maximum yields and high quality tubers. The potato plant has a high nutrient requirement due to abundant vegetative mass (Fit and Hangan 2010). Potato crops require and absorb high amounts of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca), as well as micro elements (Muhammad et al. 1989; Salah-ud-Din et al. 1997; Fit and Hangan 2010). According to Al-Jobori and Al-Hadithy (2014), micronutrients such as boron (B), zinc (Zn), manganese (Mn) and coper (Cu) are essential for plant growth and development. Poljak et al. (2007) reported that high potato yields can be achieved through the application of optimal nutrients in balanced proportions. Normally, a balanced nutrient application is essential for optimum yield and tuber quality (Akhtar et al. 2010).

According to Hiller (1995), foliar fertilisation with macro- and micro nutrients can be applied as a supplemental source of nutrition. Plant foliar fertilisation is regarded as a form of top dressing with fertiliser being applied as an aqueous solution which still remains a supplement of the basic root-applied fertilisation (Maykuhs 1988). According to Kazemi (2013), foliar application of fertilisers is based on the principle that the nutrients are quickly absorbed by leaves and transported to various plant parts to fulfil the functional requirement of nutrition. The major aim of foliar application is to enable optimum absorption of nutrients into the plant tissue (Curley 1994). Foliar application of fertilisers is ideally designed to provide nutrients in environments or under conditions that may not be conducive for optimum production, when nutrient uptake from the soil is inefficient (Hiller 1995; Boliglowa and Dzienia 1999; Kazemi 2013). Reports on the positive effects of foliar fertilisation with multi-component fertilisers include an increase in crop yield and quality of potato crops (Jablonski 2003; Mousavi et al. 2007). According to Boliglowa and Dzienia (1999), macronutrients' foliar application is recommended to increase the yield and quality of crops. However, some studies could not confirm the significant results of foliar fertilisation in potato production (Allison et al. 2001).

Calcium is an important constituent of plant tissues and has a vital role in maintaining and modulating various cell functions (Kirkby and Pilbeam 1984; Conway and Sams 1987; Hepler 2005). Tariq and Mote (2007) stated that low Ca availability could be detrimental to plant growth and yield. Calcium plays a role in the stabilisation of cellular membranes and cell walls as a component of phospholipids, thus influencing cell wall permeability (Kadir 2005). Kleinhenz et al. (1999), found that Ca concentration within the potato plants was not evenly distributed. Minute amounts of water are translocated to the tubers and this results in the low concentration of Ca in tubers compared to leaves and stems (Marschner 1995; Palta 1996). Tubers contain as little as 0.05 – 0.2 g Ca per dry mass while shoots contain up to 1.5 % Ca per dry mass (Krauss and Marschner 1973; Kempen 2012). The low concentration in potato tubers is due to the immobility of Ca in the phloem (Marschner (1995). Plant roots absorb Ca from the soil solution in the form of Ca^{2+} ions (Clarkson 1993; White 2001). Once the Ca enters the xylem it is transported via the transpiration stream and the rate and selectivity of Ca transport to the shoot is therefore predominantly controlled via the symplastic pathway (White 2001). As Ca is not phloem mobile it will not be re-translocated from old shoots to younger plant tissue (Marschner, 1995; Barker and Pillbeam 2007). Plant organs with low transpiration rates, such as potato tubers can therefore often have a low Ca content that can result in physiological disorders such as hollow heart and internal browning (Marschner 1995; Kempen 2012).

According to Sulaiman (2005), the Ca composition of tubers relies strongly on the presence of Ca in the soil solution. Calcium application after planting may thus be adequate in terms of timing in ensuring the Ca absorption by basal roots, stolon or tubers during tuber initiation or tuber bulking (Pardede 2005). Kempen (2012) reported that periderm and medulla tissue Ca composition can be supplemented by applying adequate Ca during tuber initiation and during early tuberization. The study by Ozgen and Palta (2005), revealed that Ca application in soluble forms during bulking stage results in enhancing the Ca content in non-periderm tissues. An alternative method of Ca fertilisation that is often recommended is through supplying Ca fertilisers by spraying the plants (Foliar fertiliser application) (Hiller 1995; Wójcik 2004; Saure 2005). However, the translocation of Ca into the leaves and tubers is mainly through the absorption by the root system (Krauss and Marschner 1973). Kratzke and Palta (1985) found that the xylem absorbs Ca together with water through stolons and basal roots. The rate of Ca absorption by basal roots and stolons is also proportional to the transpiration rate (Krauss and Marschner 1971). The study by Kratzke and Palta (1986) revealed that Ca application on the tuber sphere, the region of stolons and tubers resulted in a higher Ca concentration in tubers compared to when applying Ca to the basal roots. In the present study, it is hypothesised that tuber Ca concentration cannot be enhanced through foliar Ca application. Thus, the current study seeks to investigate the influence of supplemental Ca as a foliar application and a soil drench on the growth, yield and quality aspects of potatoes.

MATERIALS AND METHODS

Experimental design and treatments

The experiment was carried out in a greenhouse at Welgevallen experimental farm of Stellenbosch University, with GPS coordinates: 33°56'33.9"S 18°51'59.0"E. Seedlings, made by removing sprouting eyes from seed tubers, of two potato cultivars, Lady Rosetta and Mondial, were transplanted to 20 L (30 cm diameter) grow bags containing silica sand in a greenhouse on the 27th of April 2016 and cultivated for 64 days after planting (DAP). Mondial is widely cultivated in in Mediterranean regions, considered as a late maturing crop and is characterised by its high dry matter content (Ierna 2009). According to the Potato South Africa (2016), Mondial produces high yields of medium to large tubers with a smooth skin and shallow eyes. Lady Rosetta is a high yielding variety, with a short dormancy period, high dry matter content but it is susceptible to internal bruising (Canadian Food Inspection Agency 2013). Soil samples were taken from different pots and were tested for soil analysis before starting the experiment to check the nutrients that were already available in the soil before planting. All 70 potato plants were supplied with a standard nutrient solution containing 320 g calcium nitrate $Ca(NO_3)_2$ per $1000L^{-1}$ water as a source of Ca (Table 4.1). The experiment was a complete randomised design (CRD), 2x7 factorial arranged design, comprised of two cultivars and seven treatments, each treatment had 5 replications, which resulted in 70 plants. Additional Ca $(NO_3)_2$ was applied as a foliar and soil drench at a high (9 meq L^{-1}) or standard (6.6 meq L^{-1}) rate. Applications were made from week 6 to week 8 to coincide with the tuber initiation phase or from week 6 to week 10 to cover tuber initiation as well as early tuber filling:

F1 - Control (Only standard nutrient solution).

F2 - 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting.

F3 - 9 meq L^{-1} Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting.

F4 - 4 meq L^{-1} as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting.

F5 - 4 meq L^{-1} Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting.

F6 - 9 meq L^{-1} Ca as a foliar treatment on 6, 7 and 8 weeks after planting.

F7 - 9 meq L^{-1} Ca as a soil drench treatment on 6, 7and 8 weeks after planting.

A 2L spray pump was used to apply the foliar spray 64 days after planting (DAP). After each treatment, the pump was washed thoroughly. Treatments were arranged in a randomized complete block design with 10 replicates per treatment combination.

The pots for treatments two, four, six and seven were covered with foil during spraying of leaves so that excess foliar spray would not run down to the root zone. Each plant received whole 100 ml per week for five weeks (treatment 2 to 5) and for three weeks (treatment 6 and 7). The experiment was terminated on the 25th of July 2016.

Table 4.1. Nutrient solution composition of the baseline solution applied to all the plants. The electrical conductivity (EC) of the solution was 1.5 mS cm^{-1}.

Fertilisers	Application (g $1000L^{-1}$)
KNO_3	585.8
K_2SO_4	87.0
KH_2PO_4	108.8
$Ca(NO_3)_2.2H2O$	320.0
$MgSO_4.7H_2O$	516.6

Data collected

The influence of Ca applied as a foliar application and a soil drench on the growth, yield and quality aspects of potatoes was investigated, 64 days after planting (DAP). Crop growth, tuber yield and tuber quality were assessed. For crop growth assessment the shoot and tuber fresh mass (g) of each plant was recorded before the leaves and tuber samples were oven-dried at 82°C for 3 days. Samples were then weighed to obtain the dry mass (g). Besides fresh mass, yield was also determined per size class; Small (<20g), Medium (>20 - 80 g) and Large (>80g). Each size class was compared with other tubers within the column. Three tubers per sample were then randomly selected, peeled and sliced for the determination of chemical analysis as a quality parameter. Chemical analysis was determined through macro and trace elements method 6.1.1 for feeds and plants (Alasa 1998). Ash samples were dried overnight (78°C) and made up in a 1:1 HCl solution, filtrated and read on Inductively Coupled Plasma (ICP). Tuber analysis was done to determine the effect of Ca on other nutrient levels. These quality tests were carried out at Stellenbosch Agronomy lab and the lab at Elsenburg, Western Cape Department of Agriculture. Tuber specific gravity as an indication of the density and therefore processing quality was determined through dividing the mass of potatoes by the volume of water that overflowed when potatoes were dipped in a 2L jar filled with water. Data was analysed using analysis of variance (ANOVA), and means compared ($P<0.05$) using the general linear model of Statistica 12 software (Statistica 2012).

RESULTS AND DISCUSSION

There were no significant interactions between factors in any of the parameters tested.

Tuber yield

Average tuber fresh mass of medium tubers was not significantly influenced by foliar or soil drench Ca application (Table 4.2). Some significant differences between some of the treatments were however noticed. Plants that was treated with 9 meq L^{-1} Ca as a foliar treatment on 6, 7 and 8 weeks after planting (F6), yielded small tubers which had higher average tuber fresh mass (10.3 g $tuber^{-1}$) than tubers that was yielded by plants treated with the control (only standard nutrient solution - 6.6 meq L^{-1}), F2 and F7 (Table 4.2). Plants that was treated with 4 meq L^{-1} Ca as a soil drench on 6, 7, 8 and 10 weeks after planting (F5), yielded large tubers which had higher average total tuber fresh mass (111.0 g $tuber^{-1}$) than plants that were treated with 9 meq L^{-1} Ca as a foliar treatment on 6, 7 and 8 weeks (F6) after planting. This may be due to the availability of Ca as a result of Ca soil drench application that positively influenced the average tuber yield.

Foliar and soil drench calcium application did not influence the tuber fresh mass per plant (Table 4.3). According to Estevez et al. (1982), average tuber mass and number of tubers $plant^{-1}$ are most closely related to the tuber yield. Similar findings were obtained in the study by Clough (1994) where potato yields were not significantly influenced by Ca treatments with any cultivar that was tested. This might be due to the Ca concentration application that was sufficient or the time of Ca application was incorrect. It is also possible that no effect was noticed as the Ca concentration in the base nutrient solution was already relatively high.

Fresh tuber mass per plant was significantly higher for Mondial (304g) than for Lady Rosetta (202g) tuber fresh mass (Fig 4.1). Abu-Zinada and Moussa (2015) reported that tuber mass $plant^{-1}$ in Mondial increased significantly while Lady Rosetta yielded lower yield medium tubers (30 – 60 mm) than Mondial. According to Potato South Australia (2013) Mondial produces high yields in spring, summer and winter plantings. This trial was planted in the winter season, this suggest that Mondial yielded higher yields than Lady Rosetta due to the fact that the growing season and environmental conditions were conducive to Mondial growth.

Table 4.2: Effect of foliar spray and soil drench calcium application on average tuber fresh mass.

Treatments	Small (g $tuber^{-1}$)	Medium (g $tuber^{-1}$)	Large (g $tuber^{-1}$)	Average (g $tuber^{-1}$)
F1*	6.5b	39.7a	99.0a	103.3ab
F2	7.2b	40.1a	117.4a	101.0ab
F3	9.9ab	37.0a	51.0b	80.0ab
F4	8.0ab	33.5a	104.3a	100.0ab
F5	9.0ab	41.4a	118.4a	111.0a
F6	10.3a	33.0a	92.0ab	67.3ab
F7	7.6b	41.2a	NA	59.3b
	*	ns	*	*

Non-significant (ns). Significant (*). Treatment means followed by different letters within a column differ significantly (P<0.05).

*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4 = 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.

Table 4.3: Effect of foliar spray and soil drench calcium application on tuber fresh mass.

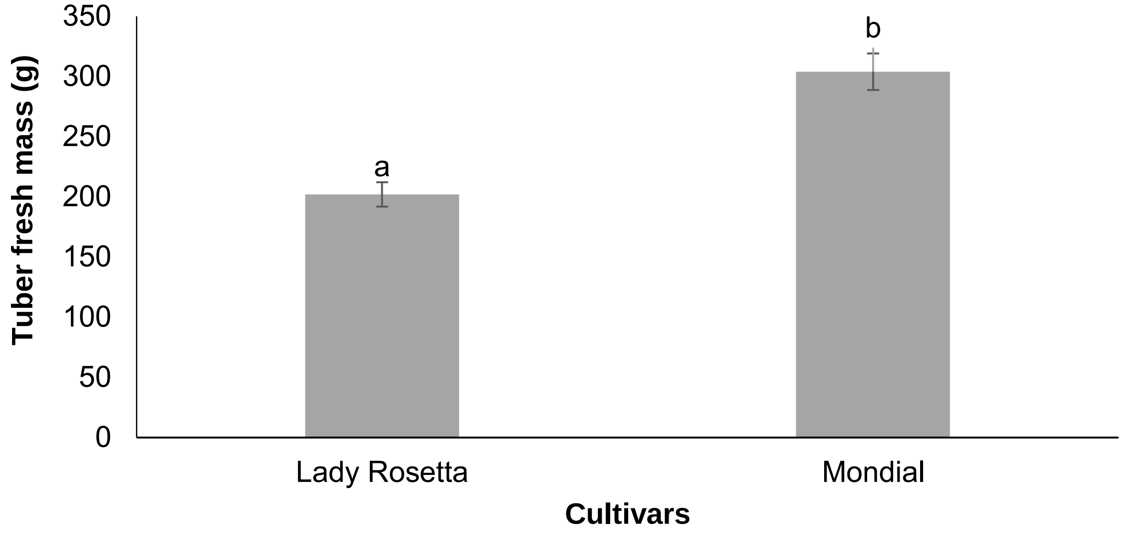
Treatments(meq L^{-1})	Small (g)	Medium (g)	Large (g)	Total tuber mass(g)
F1*	72a	164a	109a	291a
F2	57a	119a	133a	241a
F3	62a	155a	NA	254a
F4	58a	127a	97a	259a
F5	66a	161a	106a	287a
F6	90a	111a	142a	223a
F7	52a	113a	101a	216a
	ns	ns	ns	ns

Non-significant (ns).

Treatment means followed by different letters differ significantly (P<0.05).

*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4

= 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.



ANOVA	F-value	Pr>F	Significance
Cultivar	25.09796	0.0000	**

** P<0.01

Figure 4.1: Average tuber mass of Mondial and Lady Rosetta cultivar. Different letter symbols above bars indicate significant differences at $p < 0.05$.

Number of tubers

Tuber number in this trial was not significantly influenced either by foliar or soil drench Ca application (Table 4.4). This is In contrast with the findings by El-Zohiri and Asfour (2009) reported that there were significant effects on the number of tubers as a result of using foliar sprays. The results from this study are in agreement with those reported by Modisane (2007) where the number of tubers and stolons were not significantly influenced by Ca application rates. This might be due to the fact that Ca was applied during tuber formation period which is not suitable for potatoes. Ozgen and Palta (2005) reported that Ca application to the soil during the tuberization period can reduce tuber numbers. Very few large tubers were observed in all the treatments indicating that this trial was possibly terminated too early.

Table 4.4: Effect of foliar spray and soil drench calcium application on tuber number.

Treatments (meq L^{-1})	Small (g)	Medium (g)	Large (g)	Average total Number
F1*	10a	4a	1a	14.1a
F2	9a	3a	1a	11.2a
F3	13a	4a	1a	16.2a
F4	7a	3a	1a	10.1a
F5	8a	4a	1a	10.6a
F6	10a	3a	1a	12.5a
F7	8a	3a	NA	10.9a
	ns	ns	ns	ns

Non-significant (ns).

Treatment means followed by different letters differ significantly ($P<0.05$).

*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4 = 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.

Tuber specific gravity

Specific gravity (SG) measurements of individual tubers of this trial are presented in Table 4.5. Small and medium tuber SG was significantly influenced by either foliar or soil drench Ca applications, but SG of large tubers was not significantly influenced by either foliar or soil drench Ca applications. Plants sprayed with 4 meq L^{-1} as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting (F4), yielded small tubers which had higher specific gravity (1.0817) than the tubers that were obtained on the plants sprayed with 9 meq L^{-1} Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting (F3). For medium tubers, plants treated with only standard nutrient solution (F1) yielded tubers which had higher specific gravity (1.0121) than the tubers that was obtained on the plants sprayed with 9 meq L^{-1} Ca as a foliar treatment on 6, 7 and 8 weeks after planting (F6). Similar results were obtained by Awad et al. (2010) who found that foliar application of nutrients did not significantly influence specific gravity. The study by Clough (1994), revealed that specific gravity which ranged from 1.073 to 1.085 for different cultivars was not significantly affected by Ca application, though Ca plays a significant role in the quality of potatoes. The reason may be due to the inability of calcium to influence any quality aspect of tubers if it is being supplied as a foliar application as a result of Ca being immobile in the phloem. According to Murphy and Goven (1959), good specific gravity is considered as 1.0824. The importance of SG is to measure the quality of potatoes, and potato quality is directly associated with dry matter content (Myhre 1959; Davenport 2000).

Table 4.5: Effect of foliar spray and soil drench calcium application on tuber specific gravity.

Treatments(meq/L)	Small	Medium	Large
F1*	0.9106ab	1.0121a	1.0899a
F2	1.0139ab	1.0028ab	1.0537a
F3	0.7566b	1.0875ab	NA
F4	1.0817a	1.0500ab	1.0136a
F5	0.8726ab	1.0175ab	1.0527a
F6	1.0320a	0.8838b	1.0097a
F7	0.9553ab	0.9699ab	1.0914a
	*	*	ns

Non-significant (ns). Significant (*). Treatment means followed by different letters differ significantly ($P<0.05$).

*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4 = 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.

Percentage dry mass and shoot dry mass

Neither the shoot percentage dry mass nor the shoot dry mass was significantly influenced by Ca treatments (Figure 4.2; Figure 4.3). However, differences were observed among treatments in shoot dry mass. Plants treated with Control (Only standard nutrient solution) had higher shoot dry mass (19g) than all the treatments except treatments F3 and F6 (9 meq L^{-1} Ca as drench from weeks 6 to 10 and 9 meq L^{-1} Ca as foliar application from weeks 6 to 8 respectively). This is in contrast with a previous study carried out by Murillo-Amador et al. (2006) on cow pea, where foliar spray of calcium nitrate appeared to have an influence on the dry matter accumulation in the shoot.

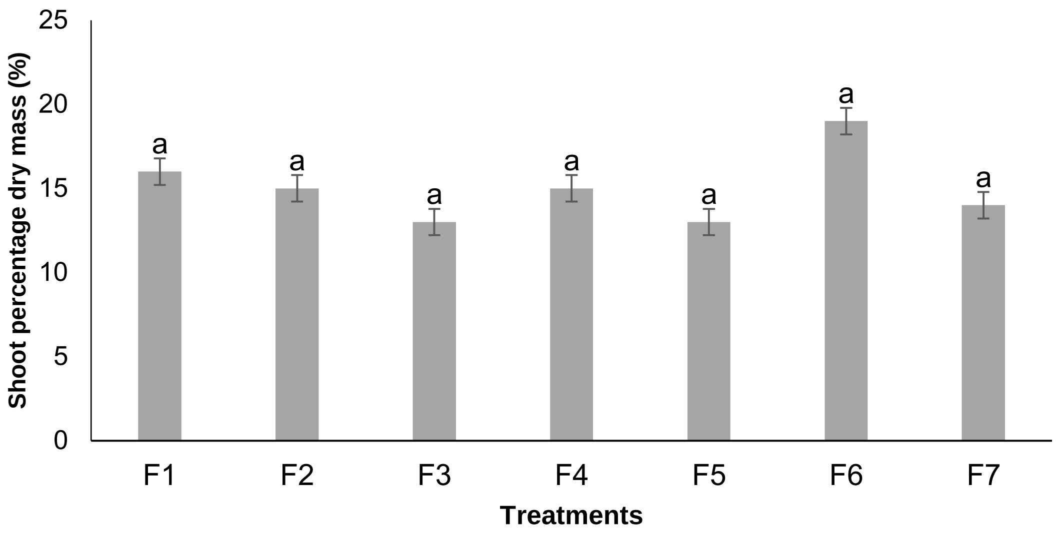
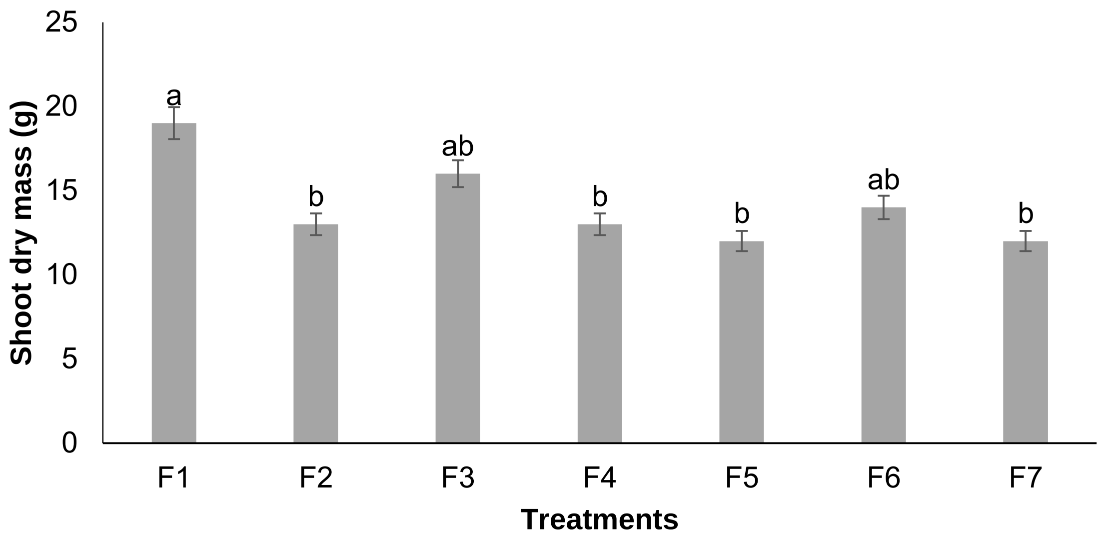


Figure 4.2: Effect of foliar spray and soil drench calcium application on shoot percentage dry mass. Different letter symbols above bars indicate significant differences at $p < 0.05$.

*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4 = 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.



ANOVA	F-value	Pr>F	Significance
Treatment	1.6335	0.1554	ns

ns, not significant at P=0.05

Figure 4.3: Effect of foliar spray and soil drench calcium application on shoot dry mass. Different letter above bars indicate significant differences at $p < 0.05$.

*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4 = 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.

Tuber nutrient content

Application of Ca as foliar or soil drench significantly influenced the concentration of phosphorus (P), potassium (K), zinc (Zn) and boron (B) but not concentration of nitrogen (N), Calcium (Ca) and Magnesium (Mg) (Table 4.6). For Potassium (K), all treatments yielded tubers which had higher potassium nutrient composition than plants treated with F7 (9 meq L^{-1} Ca as a soil drench at 6, 7 and 8 weeks after planting). Significant differences were observed in Boron (B), where plants that were treated with F2 yielded tubers which had higher B nutrient composition (9.71 mg kg^{-1}) than plants treated with F6 (9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting). Zinc and P tuber content was higher (32.50 mg kg^{-1} and 0.39% respectively) in plants treated with F2 compared to the tubers that was yielded by the plants that was treated with F3. F2 (9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting) treatment always, except for Ca, resulted in the highest concentrations of all the elements (P, K, Zn and B) (sometimes significant, sometimes not significant). These elements are found in the largest amounts in tubers because they are phloem-mobile. This is in correlation with the study by Westermann (2005), where he stated that N, P, K, Mg, and S are very mobile in the phloem.

Significant differences between the cultivars nutrient content with regards to Mg, B and Zn was observed (Figure 4.4, Figure 4.5 and Figure 4.6). Lady Rosetta yielded tubers which had a lower Mg nutrient content (0.14 mg) than Mondial (0.16 mg) (Figure 4.4). Magnesium plays a significant role in plant physiology, including a key role in chlorophyll, during the production of carbohydrates and increases potato yields and quality (Hoyum 2000; Talukder et al. 2009). Low Mg content of the tuber might be the result of Mg deficiencies which also caused low yields.

Mondial yielded tubers that had a higher B content (10.4 mg) compared to Lady Rosetta (7.6 mg) (Figure 4.5). This might be due to cultivar differences, Mondial is adapted to grow in sandy soil, which makes it easier to absorb nutrients in soil, including B. Boron plays a significant role in cell wall synthesis and seed development (Talukder et al. 2009). Mondial yielded tubers which had a higher Zn concentration content (32.4 mg) than Lady Rosetta (26.2 mg). Fernandes et al. (2015) found that the Mondial cultivar produced tubers with higher dry matter percentage and higher contents of Ca, Cu, and Zn than Agata cultivar. The study by Mohamadi (2000) revealed that application of Zn along with Mn as foliar application resulted in an increase in efficiency and quality of potato crop.

Tuber nutrient content (calcium and nitrogen) was not statistically influenced by either foliar or soil drench calcium application levels (Table 4.6). According to Palta (1996), foliar applications of Ca do not alleviate problems with Ca deficiencies in the tubers, however, it was reported that there is limited evidence that foliar applications of Ca (0.5 to 1.0 %) at the beginning of flowering improves the Ca status of the shoot, thereby enhancing crop health. The lack of reponse in tuber Ca content might be due to the immobility of Ca in the phloem which contributes to it being stored in the leaves and thereby improving the Ca status of the leaves.

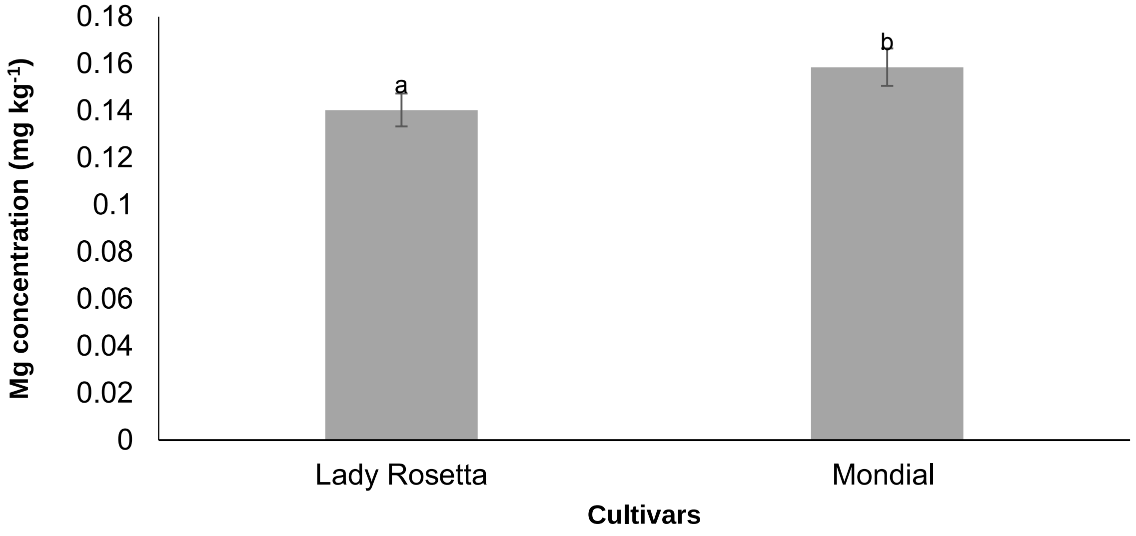
Table 4.6: Effect of foliar spray and soil drench calcium applications on the concentration of macro and micro elements in potato tubers.

Treatments	**N**	**P**	**K**	**Ca**	**Mg**	**Zn**	**B**
	%	**%**	**%**	**%**	**mg kg^{-1}**	**mg/ kg^{-1}**	**mg kg^{-1}**
F1*	1.92a	0.36ab	2.50a	0.02a	0.15a	28.79ab	9.19ab
F2	2.08a	0.39a	2.66a	0.06a	0.15a	32.50a	9.71a
F3	1.86a	0.33b	2.55a	0.03a	0.15a	26.81b	9.67a
F4	1.89a	0.35ab	2.56a	0.03a	0.14a	28.19ab	9.01ab
F5	1.92a	0.35ab	2.56a	0.03a	0.15a	27.45ab	8.99ab
F6	1.75a	0.36ab	2.56a	0.06a	0.15a	30.75ab	7.56b
F7	2.04a	0.35ab	1.97b	0.02a	0.16a	30.73ab	8.85ab
	ns	*	*	ns	ns	*	*

* *P<0.05;* Non-significant (ns).

Treatment means followed by different letters differ significantly (P<0.05).

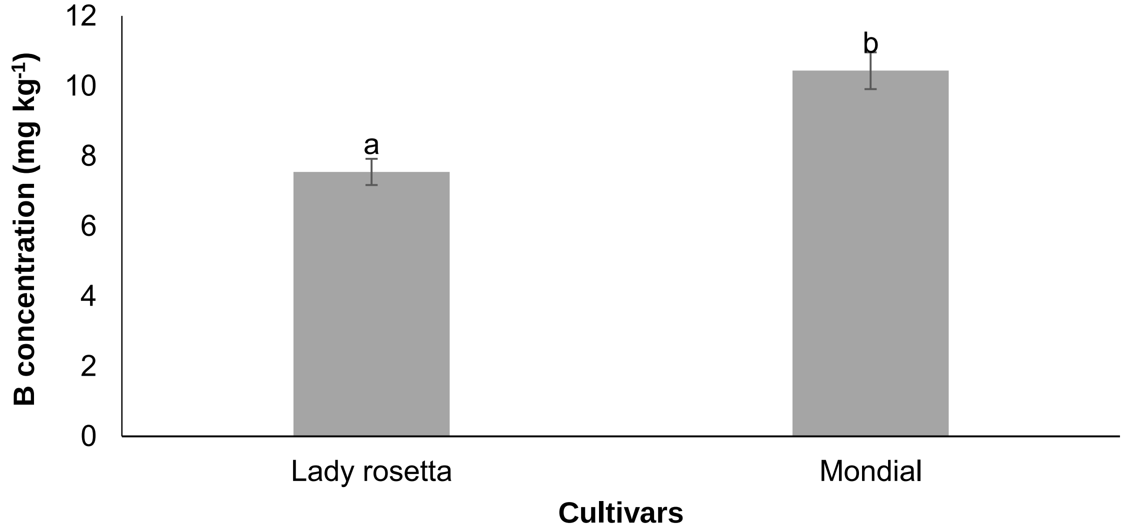
*F1 = Control, F2 = 9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F3 = Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F4 = 4 meq L-1 as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting, F5 = 4 meq L-1 Ca as a soil drench treatment on 6, 7, 8, 9 and 10 weeks after planting, F6 = 9 meq L-1 Ca as a foliar treatment on 6, 7 and 8 weeks after planting, F7 = 9 meq L-1 Ca as a soil drench treatment on 6, 7and 8 weeks after planting.



ANOVA	**F-value**	**Pr>F**	**Significance**
Cultivar	12.57	0.0016	**

** P<0.01

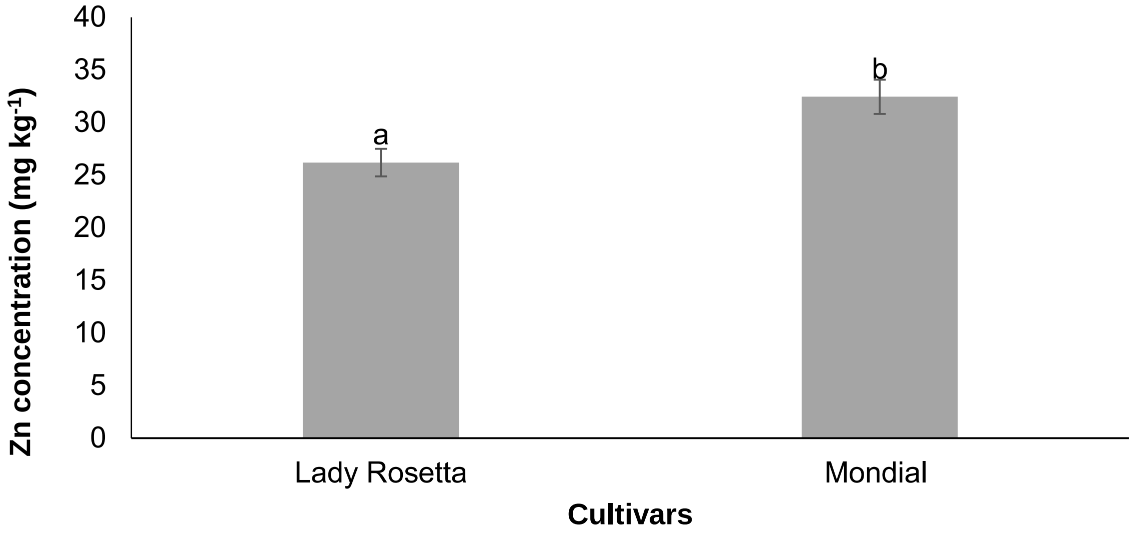
Figure 4.4: Magnesium concentration of tubers from two potato cultivars, Mondial and Lady Rosetta. Different letter symbols above bars indicate significant differences at $p < 0.05$**.**



ANOVA	**F-value**	**Pr>F**	**Significance**
Cultivar	39.6523	0.0000	**

** P<0.01

Figure 4.5: Boron concentration of tubers from two potato cultivars, Mondial and Lady Rosetta. Different letter symbols above bars indicate significant differences at $p < 0.05$**.**



ANOVA	F-value	Pr>F	Significance
Cultivar	21.0958	0.0001	**

** P<0.01

Figure 4.6: Zinc concentration of tubers from two potato cultivars, Mondial and Lady Rosetta. Different letter symbols above bars indicate significant differences at $p < 0.05$**.**

Conclusions

The tuber fresh mass, percentage shoot dry mass tuber number was not statistically influenced by either foliar or soil drench calcium application, however, specific gravity, shoot dry mass and chemical composition of tubers was statistically influenced by either foliar or soil drench calcium application. Application of nutrients through foliar sprays, specifically F2 (9 meq L^{-1} Ca as a foliar treatment on 6, 7, 8, 9 and 10 weeks after planting) increases the chemical composition of potato tubers. Mondial had higher yields and nutrient contents than Lady Rosetta. The conclusion that can be drawn from this trial is that, Ca application as foliar or soil drench did not significantly influence the yield of potato tubers because calcium cannot move from the shoot to the roots as a result of its immobility in the phloem. However, quality aspect (SG) was significantly influenced by Ca application as foliar or soil drench.

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CHAPTER 5

Summary and general conclusions

This study aimed to identify a way of improving the Ca nutrition of potato crops to improve tuber quality, yield and reduce the incidence of physiological disorders. A number of experiments were conducted at Welgevallen, Stellenbosch University Experimental farm during 2015 and 2016 to investigate the influence of nutrient solution content, various foliar fertiliser sprays and different soil types on potato tuber quality, yield and development. Different Ca application rates tend to have an influence on potato tuber yield, quality and development, but depends on the Ca application rate and on the cultivar. High calcium concentration reduces yields. Mondial yielded higher yields and Lanorma yielded high quality potatoes, this might be due to the environment which was very conducive, and most farmers prefer it. Since the first trial was planted in summer, heat stress also influenced the tuber yield positively. The root system of potatoes is poorly developed thus applying fertiliser in the tuber sphere through drip irrigation or on the leaves as a foliar application can enhance nutrient absorption. Calcium is absorbed through the root system and then transported to other parts of the plant by the transpiration process and by cation exchange capacity. However more mechanisms have been developed to increase the nutrient status within potato tubers. One of the mechanisms is fertiliser application through foliar sprays. Foliar sprays plays a vital role in supplying nutrients to meet crop needs, however calcium is phloem immobile, and it can't move from leaves to the above ground parts. Application of calcium as a soil drench plays a role in producing large tubers and plants easily absorb nutrients from the soil solution.

There are numerous other factors which can also affect potato production and quality of potatoes including low temperatures and soil type. Low temperatures during winter severely affect potato production, in such a way that low temperatures increases the incidences of diseases. Low temperatures and persistent rainfalls damages the plant foliage, and rainfall increases the incidences of leaf spots and leaf blights in potato plants. Low temperatures resulted to lower yields due to the high humidity during the growing period. High humidity affect potato production, in such a way that the moisture builds up in plants forming the waxy substances on branches which indirectly cause fungi and mildews. Plants that were grown in the sandy loam yielded higher yields. Soil pH also plays a role in the nutrient availability in the soil, if the soil is too acidic, there will be insufficient nutrients in the soil. Calcium plays a significant role in potatoes, in such a way that it protect the cells from bacterial invasion and also influence the storability of seed potatoes and quality can be indirectly improved through calcium application. Calcium can be applied to potatoes to increase the calcium content through fertigation. The environment was conducive for Mondial, Sifra and Destiny since they performed very well vegetatively, in terms of visual quality and they produced higher yields.

Applying a plant's main nutrient needs (nitrogen, phosphorus and potassium) is most effective via soil drench, although foliar application is the most recommended method of applying secondary nutrients (calcium and magnesium) and micronutrients (zinc, manganese and boron). No clear correlation was however noticed throughout the trials between the Ca application levels and the Ca content of the tubers of all the cultivars that were included in the study.

Calcium is immobile in the phloem, thus it can be recommended that calcium be applied on the root-sphere or stolon zone so that plant roots can easily absorb it. For future research, to increase the calcium content of tubers, it is essential that calcium is available in a soluble form for uptake by the stolon roots, during tuber initiation and early stages of tuber bulking. Improving potato calcium content can be done through soil drench calcium application and not through foliar application, because calcium is immobile in the phloem, thus it cannot be trans-located from the leaves to tubers. Foliar application should be applied in small quantities, because large quantities burn the foliage. There's limited research information on the use and application of foliar nutrients on potatoes, thus the future research can be focused more on evaluating the ways to improve the nutrient content, quality and tuber yields through foliar application. The future research can focus on the influence of humidity and heat stress on potato tuber yield and quality under simulated field conditions. Further research should be focused on applying calcium as a foliar spray daily but not weekly. This research serves as a reference and a guideline for future researchers and potato commercial growers that are not aware of nutrient requirement of potatoes; who want to obtain optimum yields and quality potatoes.